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A Life Cycle Assessment of Potable Water Treatment Plant

Thesis is submitted in a partial fulfillment of the requirements for the degree of Master of Science in Technology

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Tiivistelmä

Muuttuva pohjoinen ilmasto ja väestönkasvu pääkaupunkiseudulla ovat herättäneet kiinnostuksen talousvedenpuhdistusprosessin optimoimiseen. Muuttuneet ilmaston olosuhteet ovat kasvattaneet luonnollisen orgaanisen aineksen pitoisuutta Päijänne-järvessä. Luonnollisen orgaanisen aineksen kasvu on puolestaan lisännyt kemikaalien kulutusta viime vuosina ja kemikaalien kulutuksen kasvu on lisännyt puolestaan kustannuksia. Muuttuneen ilmaston lisäksi väestönkasvu pääkaupunkiseudulla on johtanut talousvedenpuhdistuksen toimimiseen lähellä sen maksimikapasiteettia.

Tutkimus on elinkaariarviointi tehostetusta perinteisestä talousvedenpuhdistusprosessista Helsingissä. Tutkimusta tullaan käyttämään vertailevassa elinkaariarvioinnissa myöhemmin, joten elinkaariarviointi on tehty siten, että se soveltuu kyseiseen tarkoitukseen. Vedenpuhdistuslaitos sisältää mm. aktiivihiilisuodatuksen, ultraviolettidesinfioinnin ja otsonoinnin. Vedenpuhdistusprosessiin tuleva raakavesi on pintavettä Päijänne-järvestä.

Elinkaariarviointi (LCA) on työkalu prosessin tai tuotteen ympäristövaikutuksien arvioinnissa. LCA on kansainvälisesti standardisoitu menetelmä, jossa selvitetään tuotteen/prosessin materiaalit, päästöt ja ympäristövaikutukset ja terveysvaikutukset tutkimuksen rajausten mukaan. Elinkaariarviointi suoritettiin ILCD-käsikirjojen mukaisesti. Elinkaariarvioinnissa käytettiin vaikutusarviointimenetelmänä keskipistemallinnusta, joka oli ReCiPe 2008 (H) Midpoint –menetelmää. Herkkyysanalyysi suoritettiin CML-Baseline-keskipistemenetelmän avulla. Elinkaariarvioinnin ohjelmistona oli OpenLCA.

Tuloksien perusteella toiminnalliset tapahtumat aiheuttivat huomattavan osan ympäristövaikutuksista, kun taas vedenpuhdistusprosessin infrastruktuuri ei aiheuttanut merkittäviä ympäristövaikutuksia. Laitoksen sähkönkulutus aiheutti suurimman osan toiminnallisten tapahtumien ympäristövaikutuksista. Lisäksi merkittäviin toiminnallisiin tapahtumiin lukeutui kemikaalien valmistus kuten kalkkimaidon, ammoniakkiveden ja natriumhypokloriitin valmistus. Kemikaalien valmistuksen ympäristövaikutus johtui maakaasun, sähkön ja kivihiilen käytöstä.

Avainsanat LCA, ILCD, ympäristövaikutus, talousvedenpuhdistus, tehostettu tavanomainen puhdistuslaitos, pintavesi, keskipistementelmä, ReCiPe 2008 (H) Midpoint, CML-baseline, OpenLCA

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Abstract of master's thesis

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Abstract

The pressure to optimize the water treatment process bases on the changing climatic conditions and population increase in the capital region. The chancing climatic conditions has lead to an increase in natural organic matter (NOM) in Lake Päijänne. NOM-concentration in turn has increased the consumption of chemicals in the past years. The increase in chemical consumption increases the costs. The population increase will result the existing water treatment plant to function near its maximum capacity.

This research is a life cycle assessment of enhanced conventional potable water treatment plant located in Helsinki. In the future, the results will be used in a comparative assertion disclosed to the public. The choices in the LCA were done in such a way that adaptation to the comparison would be possible. The plant includes granular activated carbon filtration (GAC), ultraviolet-disinfection, and ozonation. Treated raw water is surface water and it originates from Lake Päijänne.

Life Cycle Assessment (LCA) is a tool for understanding environmental impacts of a process or a product. LCA is an internationally standardized method, which describes the needed resources, emissions, environmental impacts and health impacts of the process according to scope definition. LCA was conducted according to the Handbook provided by International Reference Life Cycle Data System (ILCD). Life cycle impact assessment method was a midpoint method. Applied LCIA-method was ReCiPe (H) Midpoint and for sensitivity analysis CML-Baseline was applied. The software was OpenLCA.

The results showed operation creating most of the environmental impacts while infrastructure created significantly less impacts. The impacts of operation resulted mostly from the electricity consumption of the water treatment plant. Production of chemicals, namely limewater, ammonia water and sodium hypochlorite were the other important sources of impacts. The impacts in production of chemicals resulted from the use of natural gas, electricity, and hard coal.

Keywords LCA, ILCD, environmental impact, potable water treatment, enhanced conventional water treatment, surface water, midpoint method, ReCiPe 2008 (H) Midpoint, CML-baseline, OpenLCA

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I have spent my finest moments in Otaniemi which I will cherish the rest of my life.

Finally, thanks family & friends for your existence!

Espoo 15.11.2017

Hanna Salo

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List of Abbreviations

BACF	Biological activated carbon filtration
BC	Sum of basic cations
BS	Base saturation
CEC	Total cation exchange capacity of the soil
EESC	Effective equivalent stratospheric chlorine
ELCD	European Reference Life Cycle Database
EPA	United States Environmental Protection Agency
EPD	Environmental product declaration
ERWT	Ebro River Water Transfer
GAC	Granular activated carbon
GWP	Global warming potential
HHR	Human health risk assessment
HSY	Helsinki Region Environmental Services Authority
ILCD	International Reference Life Cycle Data System Handbook
IPCC	Intergovernmental Panel on Climate Change
IPP	Integrated product policy
LCA	Life cycle assessment
LCC	Life cycle costing
LCI	Life cycle inventory
LCIA	Life cycle impact assessment
NOM	Natural organic matter
ODP	Ozone depletion potential
ODS	Ozone depleting substances
TAP	Terrestrial acidification potential
WMO	World Meteorological Organization
WTP	Water treatment plant

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1 Introduction

The growing interest of the environment and the needs of future generations has been the driving force to investigate the environmental impacts of products and processes during their lifetime and this interest has led to the development of life cycle assessment –tool. Humans are using the resources of earth with a higher rate due to population growth and higher living standards. In the past, the water treatment technology was based on economic and technological characteristics but today environmental aspects are considered an important aspect as well. Acknowledging the environmental impacts being crucial, industry must take some responsibility to tackle the issue. The water treatment industry may be responsible, to an extent, of the environmental impacts such as resource depletion, release of pollutants to the environment by using chemicals and energy.

The research is a result of ADWATECH-project, the collaborative organization focusing on the challenges resulting from the changing Northern European climate as well as the increasing population density in the Helsinki capital region. The changing climate has led to changing NOM in Lake Päijänne, the main water reservoir for the capital region, in the past. Increasing NOM concentration has led to increase in chemical consumption in the plant. Despite higher precipitation chemical consumption, currently the water quality meets the required level. The increasing trend in NOM concentration, however, raises concern. Therefore, Helsinki Region Environmental Services Authority (HSY) is interested in surveying alternative processes. The members of ADWATECH– project are Helsinki Region Environmental Services Authority (HSY), Kemira, and Aalto-university.

The aim of the research was to conduct life cycle assessment (LCA) of enhanced conventional water treatment process located in Helsinki. LCA is an internationally standardized method that describes the needed resources, emissions, environmental impacts and health impacts of the process according to scope definition. LCA was conducted according to the handbook provided by International Reference Life Cycle Data System (ILCD Handbook). In the future, the results will be used in a comparative assertion disclosed to the public. The choices in the LCA were done in a way that adaptation to the comparison would be possible. The applied program was OpenLCA-software and databases were ELCD and Bioenergiedat. Applied LCIA-method was ReCiPe (H) Midpoint and for sensitivity analysis CML-Baseline was applied. This LCA is relaying on country and site-specific data therefore this research is not applicable to other situations although some similar conclusions might be possible to conduct.

2 Life Cycle Assessment of Potable Water Treatment

2.1 Principles of Life Cycle Assessment

Life cycle assessment (LCA) is a tool for understanding environmental impacts of a process or a product. LCA is an internationally standardized method, which describes the needed resources, emissions, environmental impacts and health impacts of the process. Life cycle assessment depicts the whole life cycle of the process which starts from the harnessing of the resources of environment, until they are recycled or deposited as waste. The lifecycle of a process includes the life cycle stages shown in Figure 1. The term cradle-to-grave implies the consideration of all the life cycle stages. (EC-JRC, 2010a.)

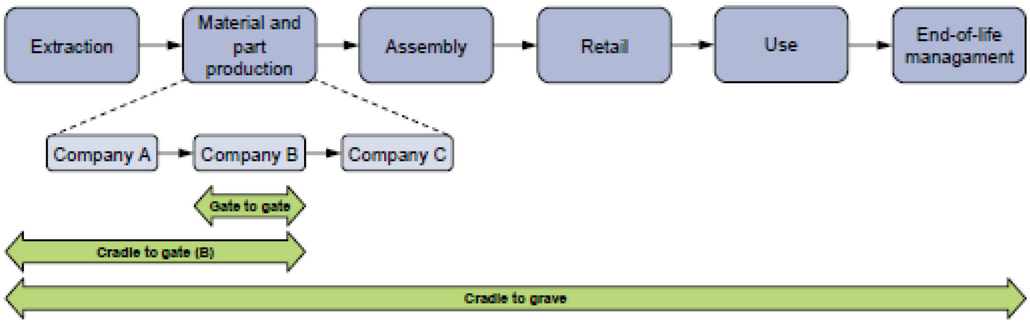


Figure 1. The life cycle stages of a process (EC-JRC, 2010a).

Exclusion of some of the life cycle stages is possible if it is insignificant considering the results. Another reason for exclusion of activities or life cycle stages is, as in the case of comparative LCA, the fact that compared processes have similarities which are therefore possible, or more over advisable, to neglect. Excluding similar activities reduces the work-load. If the exclusion might be significant, addressing the impact in the data set quality and conclusions is obligatory. (EC-JRC, 2010a.)

The steps of LCA are divided into five phases (Figure 2):

- The goal definition describes the intended application, method limitations, assumption limitations and impact limitations. These aspects determine the modelling principle and the characteristics of the data. (EC-JRC, 2010a.)
- In the scope definition the system boundaries and assumptions are set in line with the goal definition, and the selected LCIA-method is introduced (EC-JRC, 2010a).
- In the life cycle inventory analysis: inventory data is collected. This phase is thought to be the most time consuming phase. (EC-JRC, 2010a.)
- In the life cycle impact assessment, results are calculated by applying the LCIA method. The LCIA method calculates the environmental impacts of the inventory data by assigning impacts under several sub-categories, i.e. impact categories. (EC-JRC, 2010a.)
- In the life cycle interpretation, the LCIA-results are interpreted in line with the goal definition (EC-JRC, 2010a).

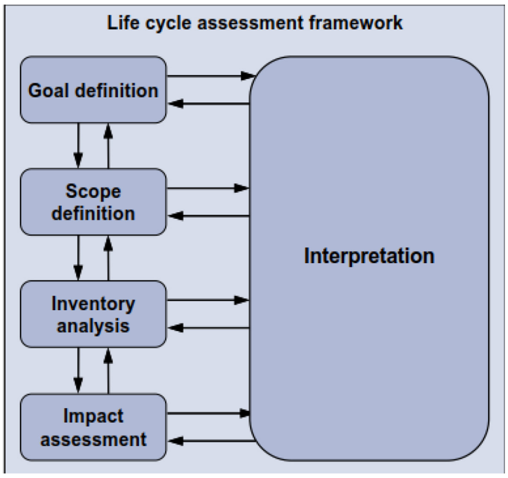


Figure 2. Phases of the LCA (EC-JRC, 2010a).

Each phase contains provisions that are either mandatory, mandatory unless exclusion is well justified, or solely a recommendation. The phases are conducted first in order, starting from the goal definition. Later on overlapping occurs since new information about the process is gathered as the LCA is conducted. (EC-JRC, 2010a.)

The ISO-standards relating to LCA are ISO:14040:2006, ISO 14044:2006, ISO/TR 14047, ISO/TS 14048 2002 and ISO/TR 14049:2000 (Antikainen, 2010). ISO:14040:2006 (ISO, 2006a) and ISO 14044:2006 (ISO, 2006b) are further discussed since this research relies partly upon them.

International reference life cycle data system (ILCD) has compiled a handbook on executing an LCA study. ILCD were developed to provide more details on compiling LCA data and executing LCA studies that are more consistent and of better quality. Problems with consistency arose since the ISO standards, ISO 14040 and 14044, offered the individual practitioner a range of choices to choose from therefore possibly affecting the robustness of the results. ILCD consists of guidance documents, ILCD Handbook, and the ILCD Data Network. The ILCD Handbook have been compiled based on the ISO 14040 and 14044 standards, LCA manuals, LCA literature and insights of the experts. The ILCD Handbook fulfills the requirements of the ISO 14040 and 14044:2006 as it is a stricter guidance document. (EC-JRC, 2010a.) The ILCD Handbook demands that the practitioner of the LCA has sufficient documentation and reasoning behind the choices (EC-JRC, 2010a).

2.2 OpenLCA

The LCA-software is OpenLCA 1.5.0. OpenLCA is developed by GreenDelta and it is an open source software. The software can be used for LCA, life cycle costing (LCC), social life cycle assessment, carbon & water footprints, environmental product declaration (EPD), United States Environmental Protection Agency (EPA) Design for the Environment label, and integrated product policy (IPP). (GreenDelta, 2016a.)

2.3 European Reference Life Cycle Database and Bioenergiedat

Collecting inventory data for life cycle inventory phase is time consuming since the availability of the data might be sometimes problematic. In order to reduce the amount of work required to compile the data, databases were developed (EC-JRC, 2010a; Antikainen, 2010).

Available databases are mostly in English but few databases are in German and in Japanese. Most countries work on developing national databases (Finnveden et al., 2009). Databases are 1) free and vast databases, 2) free specific databases, and 3) chargeable databases. Vast database consists data from several branch of industry. Another source for inventory data is free country specific input-output models, added with environmental information. (Antikainen, 2010).

Free and vast databases consist data on products and services, such as raw materials, production of electricity, transportation, and waste management. The development of databases is partly funded by public resources. The purpose of such databases is to provide national representativeness and data for everyone. Free and vast databases are SPINE@CPM database, U.S. Life-Cycle Inventory (LCI) database, European Reference Life Cycle Database (ELCD), and PROBAS database. (Antikainen, 2010.)

ELCD is continuously under development and one of the most popular databases. (Antikainen, 2010). ELCD 3.3 contains information about over 503 processes (GreenDelta, 2016b). The business associations in the EU-level and other sources provided the inventory data for the database. 190 datasets in ELCD 3.2 fulfill the ILCD Data Network entry-level data quality requirements. The ILCD Data Network Entry-Level requirements review provides information on data quality, guarantee minimum extent of documentation and methodological consistency among data sets. (OpenLCA Nexus, 2017a.)

Bioenergiedat is a database for supply chains for bioenergy alternatives and it has specific German background. The database was created in the German BioEnergieDat project. Approximately 180 datasets provide data on conversion and provision of bioenergy fuels from wood, wastewood, wheat, and biowaste. (OpenLCA Nexus, 2017b.)

2.4 Life Cycle Impact Assessment Methods

Life cycle impact assessment method (LCIA-method) calculates the environmental impacts of the inventory data and the calculation is performed, depending on the chosen method, in the midpoint level or in the endpoint level. Some methods can calculate impacts on both levels. The LCIA-modelling was originally performed in the midpoint level but later modelling in the endpoint became possible (Antikainen, 2010; EC-JRC, 2010a). There are several impact categories in the midpoint level while in the endpoint level the impacts are divided into three areas of protection: human health, natural environment and natural resources (EC-JRC, 2010a). In the endpoint modelling the environmental impacts are related to damages and in the midpoint level the impact is a potential environmental impact. (Antikainen, 2010.)

There is four steps in LCIA: selection of impact categories and classification, characterisation, normalisation and weighting. The first two are mandatory, whereas the latter two are voluntary (ISO, 2006b). The process of LCIA-methodology is in Figure 3. In the selection of impact categories and classification, first the relevant impact categories (human toxicity, acidification, etc.) are selected. After the selection of impact categories, the LCIA-method assigns the elementary flows (resource consumption, emissions, etc.) that have been gathered in the life cycle inventory phase, to impact categories. The elementary flow might be assigned to several impact categories since the flow can contribute to several environmental problems. In the next step, in characterization, the impact of resource consumption or emission will be modelled quantitatively based on the environmental mechanism, cause-effect chain, and the impact is demonstrated with characterization factor. The characterization factor converts the impact to the common unit of the impact category indicator. For example in the impact category climate change the characterization factor for CO_2 is 1 kg of CO_2-equivalents while for methane the characterization factor is more than 20 kg of CO_2-equivalents. In normalization, the characterized impact scores are associated to a reference for example per person during a year. In weighting the impact categories or areas of protection are valued according to their importance subjectively. (ISO, 2006b.)

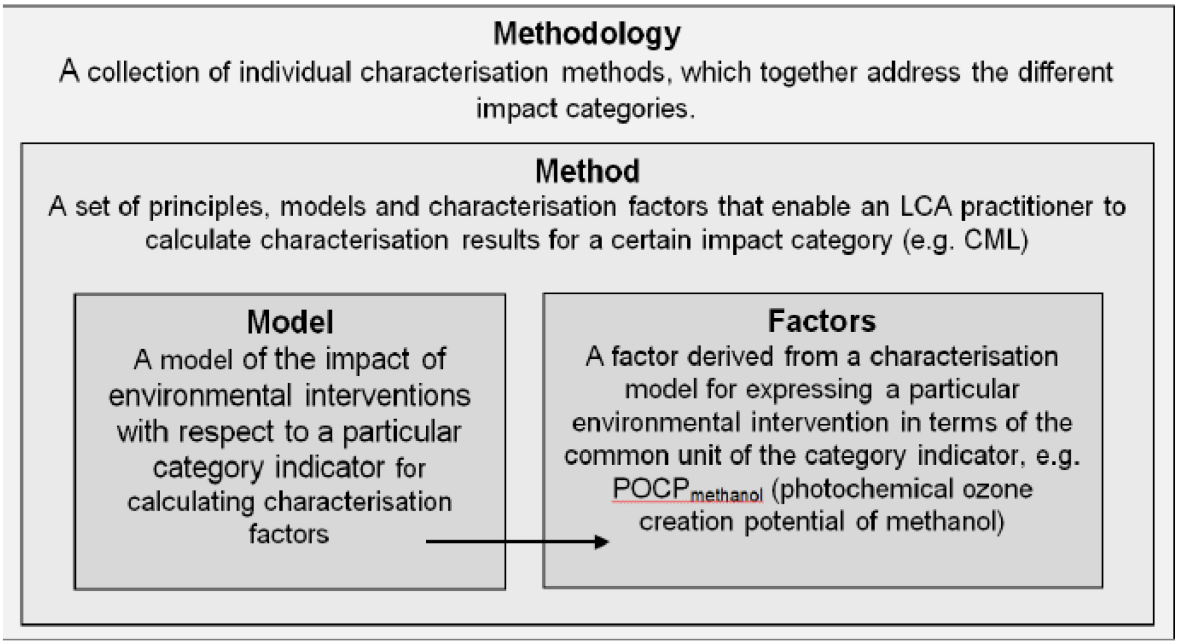


Figure 3. The process of LCIA-methodology (EC-JRC, 2011).

Although there are similarities in methods, the differences can be considerable, especially in toxicity assessment. With great differences, the application of one method over another can influence the results. (Finnveden et al., 2009.) The results from the endpoint modelling is considered less reliable as in the midpoint modelling (Antikainen, 2012; EC-JRC, 2010a; Finnveden et al., 2009; EC-JRC, 2011) although acidification and cancer related impact categories are thought to be as reliable as in midpoint modelling. The loss of preciseness is due to assumptions done in the cause-effect chain. (Finnveden et al., 2009). In addition, Finnveden et al. (2009) argues the modelling of damages being uncertain and unreasonable in the endpoint since the indicator related to environmental impacts is chosen as if after the midpoint the modelling is considered being uncertain and unreasonable. More information of the cause-effect chain of environmental impacts will be provided in the following paragraph.

In the midpoint modelling, the evaluation of environmental impact occurs in between the emission and the damage, in the “midpoint” (Antikainen, 2012). The midpoint level exists where a common mechanism for a variety of substances occurs within the impact category (EC-JRC, 2010b). For example, acidification is modelled as the potential transportation of protons instead of species (Antikainen, 2012). The categories in the midpoint level and the damages in the endpoint level are shown in Figure 4. There is many impact categories in midpoint modelling: climate change, (stratospheric) ozone depletion, human toxicity, respiratory inorganics, ionizing radiation, (ground-level) photochemical ozone formation, acidification (terrestrial, aquatic), eutrophication (aquatic, terrestrial), ecotoxicity (aquatic, terrestrial), land use, resource depletion (water, minerals, fossil, renewable energy resources) (EC-JRC, 2010b). The midpoint modelling is still in favour among the LCA community (Antikainen, 2012).

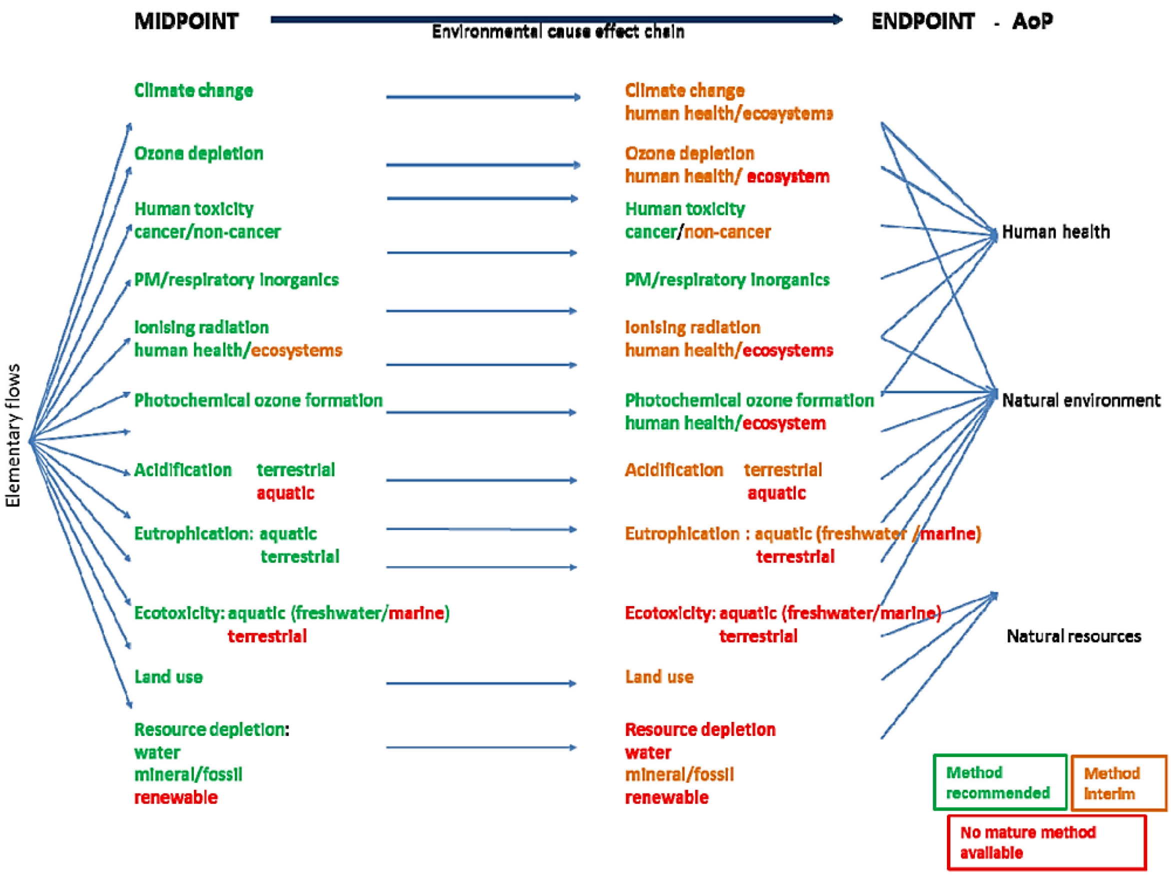


Figure 4. The categories in the midpoint level and the damages in the endpoint level (Sala et al., 2012).

Some of the categories are still uncertain since there is not a method to model them (Antikainen, 2012; EC-JRC, 2011). Antikainen (2012) argues that this is the case in toxicity, accidents, land use, desiccation, salination and resource depletion.

According to ILCD-handbook (Table 1, Table 2) there is more impact categories without appropriate model (EC-JRC, 2011). ILCD has evaluated LCIA-methods against certain criteria and recommended some methods over others. Before analyzing the methods, a pre-selection was made. The pre-selection excluded LCIA-methods and the exclusion was justified with two explanations. Other justification was the method being the same as in some other LCIA-methods and not being the most recent version. Another justification was the method being adapted to other regions while not being improved or changed in a significant way. (EC-JRC, 2010c, p.63.) The methods were evaluated against general criteria and specific criteria. The general criteria is same for all impact categories and bases on general requirements for the LCIA methods. The general criteria is divided to scientific criteria and stakeholder acceptance criterion. The scientific criteria includes completeness of scope, environmental relevance, scientific robustness and certainty, documentation, transparency, reproducibility and applicability. The specific criteria are complementary to general criteria and they are addressing the characteristic features of each individual impact category. (EC-JRC, 2011.)

The recommended methods are divided based on their quality to level I, II and III. A mixed classification can sometimes refer to different types of substances. Level I signifies the method being recommended and satisfactory. Methods may need to fulfill further research needs but are satisfactory at the moment. Level II signifies the method is recommended but in need of some improvements. The uncertainty of the models and characterization factors needs to be addressed. More over the impact on the results and interpretation has to be more carefully evaluated, especially in comparisons to be published. Level III signifies the method to be recommended but to be applied with a caution. The models need further investigation before applied without reservation for decision support, especially in comparative assertions. It is recommended to calculate the environmental impacts with and without level III methods and compare them. The method can also be immature which means that the method is best among the considered methods but not enough to be recommended. Immature method is to be applied with extreme caution and can be used only in in-house applications. (EC-JRC, 2011.)

Table 1. Recommended methods at midpoint and their classification according to ILCD Handbook (EC-JRC, 2011).

	Recommendation at midpoint		
Impact category	**Recommended default LCIA method**	**Indicator**	**Classification**
Climate change	Baseline model of 100 years of the IPCC	Radiative forcing as Global Warming Potential (GWP100)	I
Ozone depletion	Steady-state ODPs 1999 as in WMO assessment	Ozone Depletion Potential (ODP)	I
Human toxicity, cancer effects	USEtox model (Rosenbaum et al, 2008)	Comparative Toxic Unit for humans (CTU_h)	II/III
Human toxicity, non-cancer effects	USEtox model (Rosenbaum et al, 2008)	Comparative Toxic Unit for humans (CTU_h)	II/III
Particulate matter/Respiratory inorganics	RiskPoll model (Rabl and Spadaro, 2004) and Greco et al 2007	Intake fraction for fine particles (kg PM2.5-eq/kg)	I
Ionising radiation, human health	Human health effect model as developed by Dreicer et al. 1995 (Frischknecht et al, 2000)	Human exposure efficiency relative to U^{235}	II
Ionising radiation, ecosystems	No methods recommended		Interim
Photochemical ozone formation	LOTOS-EUROS (Van Zelm et al, 2008) as applied in ReCiPe	Tropospheric ozone concentration increase	II
Acidification	Accumulated Exceedance (Seppälä et al. 2006, Posch et al, 2008)	Accumulated Exceedance (AE)	II
Eutrophication, terrestrial	Accumulated Exceedance (Seppälä et al. 2006, Posch et al, 2008)	Accumulated Exceedance (AE)	II
Eutrophication, aquatic	EUTREND model (Struijs et al, 2009b) as implemented in ReCiPe	Fraction of nutrients reaching freshwater end compartment (P) or marine end compartment (N)	II
Ecotoxicity (freshwater)	USEtox model, (Rosenbaum et al, 2008)	Comparative Toxic Unit for ecosystems (CTU_e)	II/III
Ecotoxicity (terrestrial and marine)	No methods recommended		
Land use	Model based on Soil Organic Matter (SOM) (Milà i Canals et al, 2007b)	Soil Organic Matter	III
Resource depletion, water	Model for water consumption as in Swiss Ecoscarcity (Frischknecht et al, 2008)	Water use related to local scarcity of water	III
Resource depletion, mineral, fossil and renewable[6]	CML 2002 (Guinée et al., 2002)	Scarcity	II

Table 2. Recommended methods at endpoint level and their classification according to ILCD Handbook (EC-JRC, 2011).

	Recommendation from midpoint to endpoint		
Impact category	**Recommended default LCIA method**	**Indicator**	**Classification**
Climate change	No methods recommended		interim
Ozone depletion	No methods recommended		interim
Human toxicity, cancer effects	DALY calculation applied to USEtox midpoint (Adapted from Huijbregts et al., 2005a)	Disability Adjusted Life Years (DALY)	II/interim
Human toxicity, non-cancer effects	No methods recommended		interim
Particulate matter/Respiratory inorganics	DALY calculation applied to midpoint (adapted from van Zelm et al, 2008, Pope et al, 2002)	Disability Adjusted Life Years (DALY)	I/II
Ionising radiation, human health	No methods recommended		interim
Ionising radiation, ecosystems	No methods recommended		
Photochemical ozone formation	Model for damage to human health as developed for ReCiPe (Van Zelm et al, 2008)	Disability Adjusted Life Years (DALY)	II
Acidification	No methods recommended		interim
Eutrophication, terrestrial	No methods recommended		
Eutrophication, aquatic	No methods recommended		interim
Ecotoxicity (freshwater, terrestrial and marine)	No methods recommended		
Land use	No methods recommended		interim
Resource depletion, water	No methods recommended		
Resource depletion, mineral, fossil and renewable	No methods recommended		interim

2.4.1 ReCiPe 2008 Midpoint (H) Hierarchial

ReCiPe 2008 is based on CML 2002 and Eco-indicator 99. Almost all the impact categories from CML 2002 and Eco-indicator 99 have been redeveloped, an exception being ionizing radiation. Recipe accounts impacts for climate change, ozone depletion, terrestrial acidification, freshwater eutrophication, marine eutrophication, human toxicity, photochemical oxidant formation, particulate matter formation, terrestrial ecotoxicity, freshwater ecotoxicity, marine ecotoxicity, ionizing radiation, agricultural land occupation, urban land occupation, natural land transformation, depletion of fossil fuel resources, depletion of mineral resources, depletion of freshwater resources. (EC-JRC, 2010c.)

There is three perspectives in ReCiPe: individualist (I), hierarchist (H), and egalitarian (E). The perspectives contain similar assumptions and choices. Perspective I is assuming short timeframe, undisputed impacts and technological optimism related to human adaptation. Perspective H is based on the most common policy principles. The hierachist perspective means that some impacts can be avoided with proper management while total adaptability is not considered. The choice on what to include to the model is done based on scientific consensus. Perspective E is the most cautious principle with a long timeframe and impacts that are not yet fully established. Differences in assumptions between the perspectives are shown in Table 3. (Goedkoop et al., 2009.)

Table 3. Differences in assumptions between perspectives (Goedkoop et al., 2009).

To midpoint impact category:	Perspectives I	H	E
climate change	20-yr time horizon	100 yr	500 yr
ozone depletion	–	–	–
terrestrial acidification	20-yr time horizon	100 yr	500 yr
freshwater eutrophication	–	–	–
marine eutrophication	–	–	–
human toxicity	100-yr time horizon organics: all exposure routes metals: drinking water and air only only carcinogenic chemicals with TD_{50} classified as 1, 2A, 2B by IARC	infinite all exposure routes for all chemicals all carcinogenic chemicals with reported TD_{50}	infinite all exposure routes for all chemicals all carcinogenic chemicals with reported TD_{50}
photochemical oxidant formation	–	–	–
particulate matter formation	–	–	–
terrestrial ecotoxicity	100-yr time horizon	infinite	infinite
freshwater ecotoxicity	100-yr time horizon	infinite	infinite
marine ecotoxicity	100-yr time horizon sea + ocean for organics and non-essential metals. for essential metals the sea compartment is included only, excluding the oceanic compartments	infinite sea + ocean for all chemicals	infinite sea + ocean for all chemicals
ionising radiation	100-yr time horizon	100,000 yr	100,000 yr
agricultural land occupation	–	–	–
urban land occupation	–	–	–
natural land transformation	–	–	–
water depletion	–	–	–
mineral resource depletion	–	–	–
fossil fuel depletion	–	–	–

The impact categories of climate change, depletion of ozone and terrestrial acidification are presented as examples. Goedkoop et al. (2009) presents other impact categories.

2.4.1.1 Climate Change

Impact category for climate change is using indicator global warming potential developed by Intergovernmental Panel on Climate Change (IPCC). The method uses IPCC equivalence factors from the report of 2007 for characterization factors. Climate change models evaluate environmental impacts according to the chosen policy scenario. The scenarios are using different timeframes: 20, 100 or 500 years. The impacts are calculated according to the timeframe. In ReCiPe (H), the method is a baseline model of 100 years of the IPCC and the equivalence factors are from the report of 2007. The choice of timeframe does not affect the characterization factor but it does affect the importance of methane and NF_3. Global warming potential is characterized by CO_2 equivalency factors. (Goedkoop et al., 2009.) The global warming potential (GWP) is calculated for a substance x with the following formula:

$$GWP_{x,T} = \frac{\int_0^T a_x \times [x(t)]dt}{\int_0^T a_r \times [r(t)]dt} \quad \text{(IPCC, 2007)}$$

T = time horizon over which the calculation is done.
a_x = radiative efficiency due to a unit increase in atmospheric abundance of the substance
[x(t)] = time-dependent abundance of substance x
a_r = radiative efficiency due to a unit increase in atmospheric abundance of the reference gas
[r(t)] = time-dependent abundance of reference gas

The global warming potential of a substance expresses integrated forcing of a mass of a substance relative to the integrated forcing of same amount of mass of the reference gas in certain time horizon. (Goedkoop et al., 2009).

2.4.1.2 Ozone Depletion

The characterisation factor for ozone depletion is a steady state ozone depletion potential (ODP) in the midpoint level. In the calculations, some assumptions are made, especially important assumption is related to different policy options. Policy option determines in what time scale and in what amounts ozone depleting substances, ODS, are decreased (Goedkoop et al., 2009). In this method, the emissions of the ODS is considered to follow A1, "the best guess scenario", which is supported by World Meteorological Organization (WMO, 2002, p.1.63). The emission scenario is shown in Figure 5.

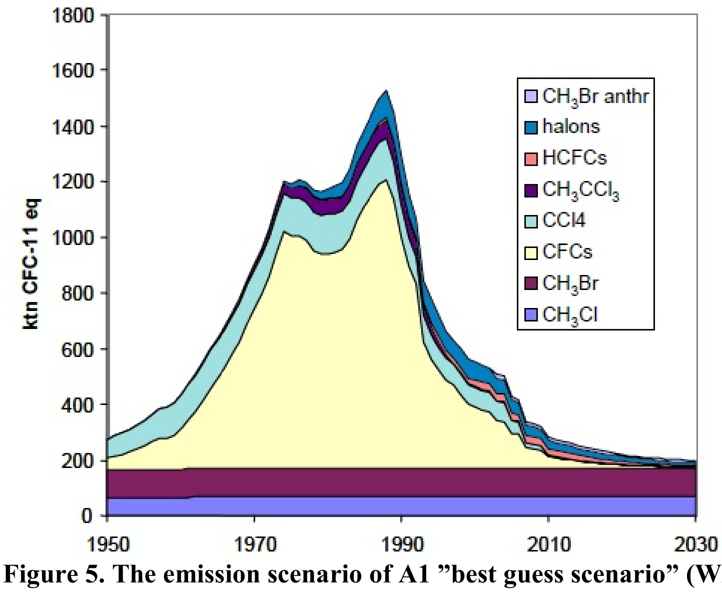


Figure 5. The emission scenario of A1 "best guess scenario" (WMO, 2002).

The stratospheric ozone is depleted by anthropogenic emissions of ozone depleting substances (ODS). Ozone depletion potential (ODP) indicates the ozone depletion capacity of an ozone depleting substance (ODS) and CFC-11 (trichlorofluoromethane) is used as a reference. Steady state ODP includes the atmospheric residence time, in the troposphere and stratosphere, the formation of EESC and the resulting stratospheric ozone depletion. (Goedkoop et al., 2009). The EESC is an effective equivalent stratospheric chlorine and it represents a rough estimate for ozone recovery in an unchanging atmosphere. The amount of EESC is numerically simulated basing on the natural and anthropogenic ODS emissions. (WMO, 2002.) A constant ratio is assumed between ΔEESC, effective equivalent stratospheric chlorine, and the resulting depletion of stratospheric ozone. ODP values are identical to "updated model-derived" and "updated semi-empirical" ODPs that is introduced by the WMO report from 2002. The estimate of EESC basing on scenario A1, ODS policy, is shown in Figure 6.

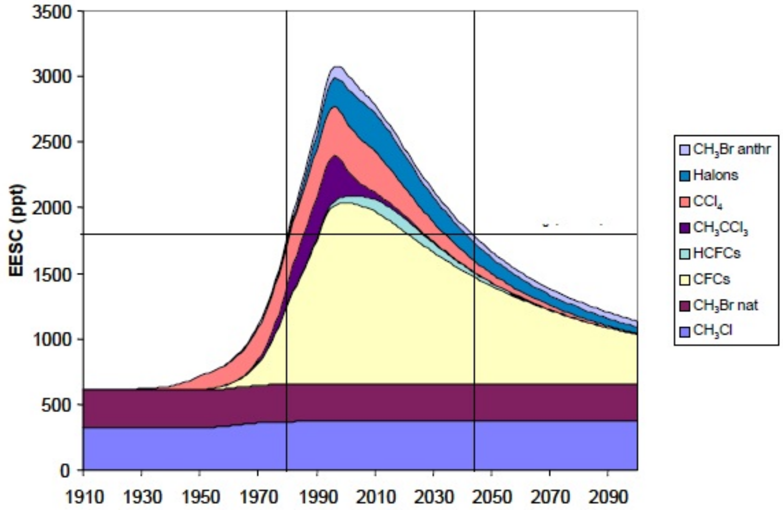


Figure 6. The concentration of EESC caused by natural and anthropogenic emissions in scenario A1. The horizontal line is the threshold concentration of the year 1980 (WMO, 2002).

2.4.1.3 Terrestrial Acidification

The indicator in a midpoint uses the Base saturation method developed by Van Zelm et al. (2007). The method calculates the atmospheric fate with the EUTREND model (Van Jaarsveld et al., 1997) and considers only terrestrial ecosystems. SMART 2 (Kros, 2002), simulation model for acidification´s regional trends, is used to characterize soil sensitivity as a change in soil base saturation.

Base saturation (BS), indicator for acidification, is the capacity of the soil to adsorb basic cations. The base saturation is calculated with the following equation:

$$BS = \frac{BC}{CEC} = \frac{[K]+[Ca]+[Mg]+[Na]}{[H]+[K]+[Ca]+[Mg]+[Na]} \quad \text{(de Vries et al., 2002)}$$

BC = sum of basic cations
CEC = total cation exchange capacity of the soil

Fate factor dBS/dM is used in midpoint level and a location–independent fate factor is used for acidification:

$$FF_x = \frac{\sum_j (\Delta BS_j \times A_j)}{\Delta M_x}$$

A_j = size of the forest area
ΔBS_j = change in the base saturation

ΔM_x = change in the emission of acidifying substance x

After calculation of fate factor the terrestrial acidification potential (TAP) is calculated with the following equation:

$$TAP = \frac{FF_x}{FF_{SO_2}}$$

2.5 Previous Research On Life Cycle Assessment of Potable Water Treatment

There is a few life cycle assessments of potable water treatment but making conclusions about them is challenging since site-specific assumptions influence greatly on the LCA (Vince et al., 2008). There is discrepancies in assumptions, life cycle inventory assessment -methods (LCIA-methods), inventory data, spatial differences and, in general, there is problems in transparency (Bonton et al., 2012; Vince et al., 2008; Igos et al., 2014). Bonton et al. (2012) argues that the even in the same comparative LCA the drinking water quality might be different which could lead to problems in comparison. In addition, the raw water quality is another aspect to consider when comparing different LCAs (Bonton et al., 2012; Vince et al., 2008). For example reverse osmosis varies according to feedwater salinity and the amount of coagulation chemical vary according to suspended matter in the raw water (Vince et al., 2008). However if the drinking water quality in both of the compared processes fulfills the legal requirements, the change in the quality might not be as important aspect. It might be worthwhile to consider how the processes will be runned in practice, as long as the minimum requirements are fulfilled, rather than producing complex and artificial arrangements so that the compared processes function identically in the modelling phase.

Igos et al. (2014) estimated the environmental impacts in a unit process level of two water treatment processes both supplied with powdered activated carbon and ultrafiltration. The research concentrated on the division of environmental impact in a unit process level between infrastructure and operation as well as the contribution of sludge both of which had been neglected in many articles. Two LCIA-methods were used: Recipe (midpoint) and Impact 2002+. Most of the environmental impacts resulted from electricity generation, activated carbon production, iron chloride production and construction of infrastructure. The chosen LCIA-method influenced the results highly which is shown in Table 4. With Recipe the electricity generation contributed 28 % and 23 % of the total environmental impacts, depending on the treatment plant, whereas with Impact 2002+ the contribution was 49 % and 50 % of the total environmental impacts. The activated carbon production contributed 26 % and 31 % of the total environmental impacts with Recipe whereas with Impact 2002+ the contribution was 13 % and 19 %. The iron chloride production contributed 19 % and 11 % of the total environmental impacts with Recipe whereas with Impact 2002+ the contribution was 11 % and 6 %. The construction of infrastructure contributed 12 % and 7 % of the total environmental impacts with Recipe whereas with Impact 2002+ the contribution was 5 % and 4 %. By using Impact 2002+ as LCIA-method the contribution of electricity generation is double the impact that of by using Recipe. In contributors such as activated carbon, iron chloride production and construction of infrastructure the impact in Recipe is double the impact of Impact 2002+. This research clearly showed the difference in the results between two LCIA-methods.

Table 4. The contribution in percents to total environmental impacts divided by activity and LCIA-method. The results for Site A and B are not comparable since the plant are providing different potable water qualities by treating different sources of raw water.

Contributor	Treatment plant	Recipe %	Impact 2002+ %
electricity generation	site A site B	28 23	49 50
activated carbon production	site A site B	26 31	13 19
iron chloride production	site A site B	19 11	11 6
construction of infrastructure	site A site B	12 7	5 4

Compared to other publications the contribution of electricity consumption is lower especially with Recipe that has a higher impact of activated carbon. In addition, for both methods additional explanation could be the increasing use of reagents because of poor water quality. Overall most of the impacts originate from fossil resource use in electricity and activated carbon. The contribution of infrastructure, although production phase of the devices excluded, was similar as in Bonton et al. (2012) and Raluy et al. (2005a). Since the water quality is poor, the water treatment process is advanced. This fact needs to be considered if another treatment process is run under lower operation conditions the contribution of infrastructure might be higher. (Igos et al., 2014.)

Ribera et al. (2014) compared conventional treatment versus conventional treatment with nanofiltration treatment. The research combined LCA ReCiPe Midpoint (H) (Figure 7) and HHR (Figure 8) together. The results of Recipe Midpoint (H) are shown in Figure 7. The percents imply the amount of water filtered through nanomembranes. The more the water was nanofiltered, the more the environmental impact but simultaneously human toxicity decreased according to HHR (Figure 8). The ozone depletion and metal depletion increased the most. The environmental impact in most of the impact categories increased about 50 % in nanofiltration processes compared to conventional process.

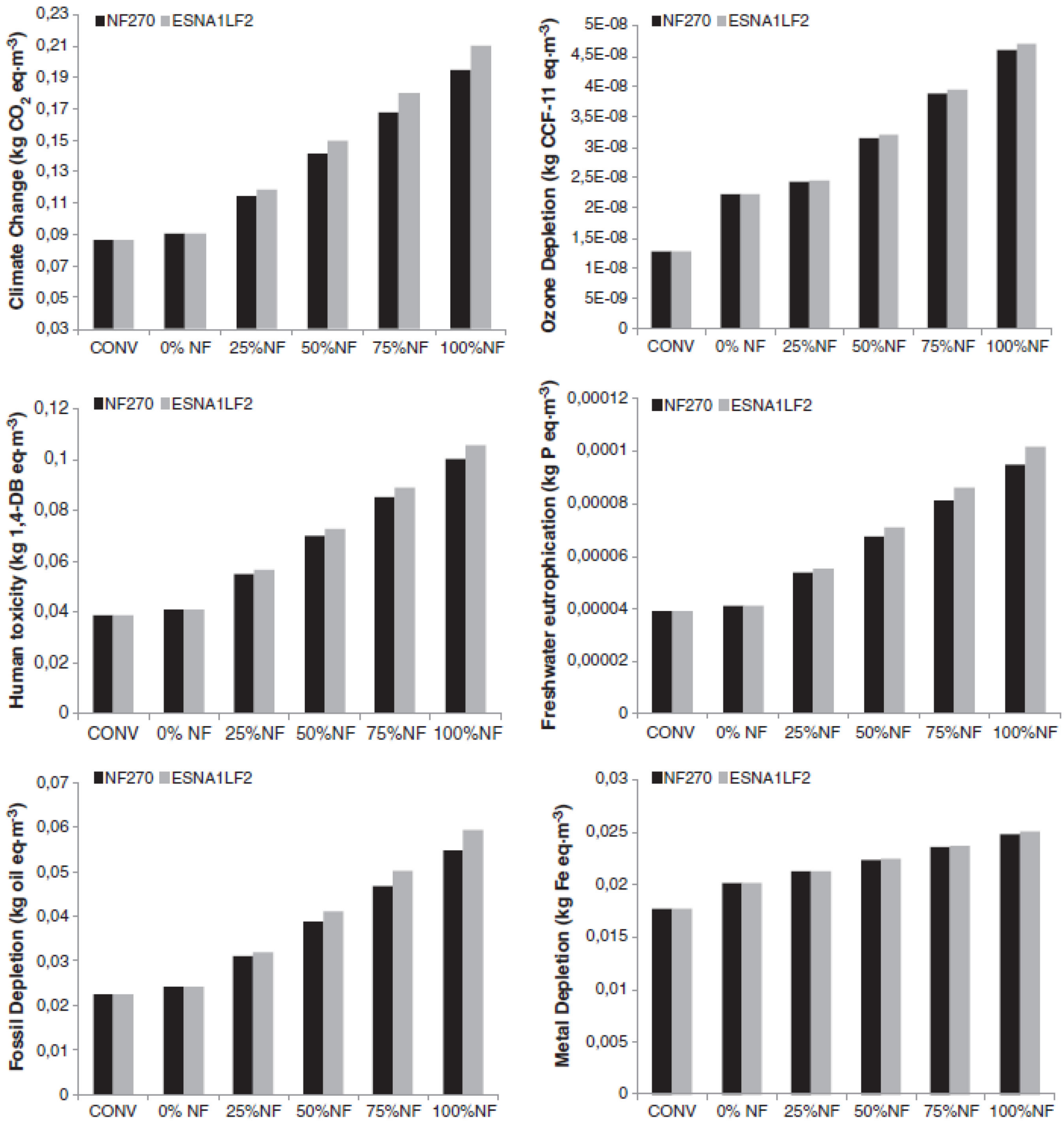


Figure 7. The environmental impact of different water treatment scenarios with Recipe Midpoint (H) (Ribera et al., 2014).

From Figure 7 and Figure 8, one can see the contradiction in the human toxicity between Recipe Midpoint and HHR. In Recipe the human toxicity increases with nanofiltration while in HHR the human toxicity decreases. The methods contradict each other in human toxicity. (Ribera et al., 2014.)

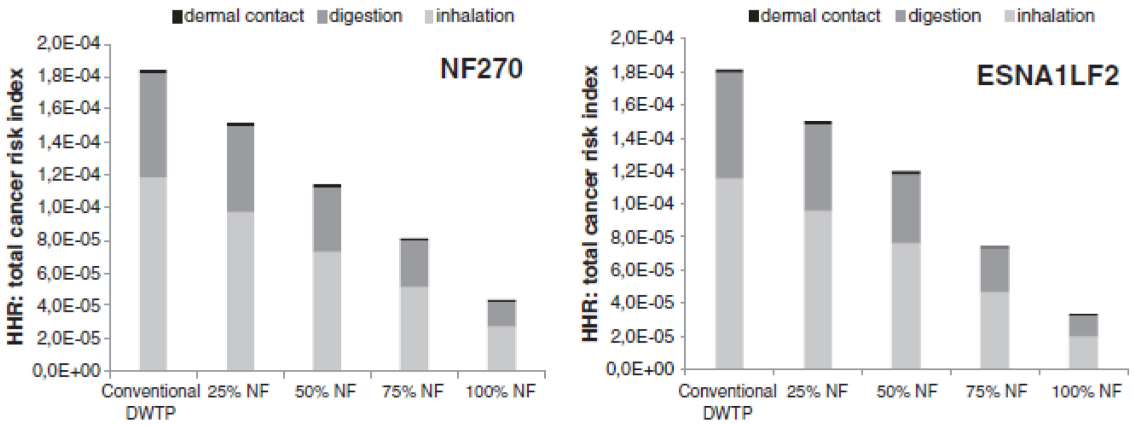


Figure 8. HHR as method: Sum of the carcinogenic risk index for different exposure pathways: inhalation, digestion, and dermal contact (Ribera et al., 2014).

Raluy et al. (2005a) compared the environmental impacts of three desalination technologies for potable water production. The LCA was done in SimaPro and three different LCIA-methods were used: CML 2 Baseline 2000, Eco-Indicator 99 and Ecopoints 97. Table 5 presents the impact categories chosen in each LCIA-method. The operational, construction and demolition phases were included but the impact of concentrate was excluded. In all the LCIA-methods, the operational phase had the highest contribution to the environmental impacts while construction and decommissioning phases were negligible. The operational phase dominated with contribution of 88.6-99 % and the construction and demolition phases contributed only with 1-11.4 %.

Table 5. Included impact categories within a certain LCIA-method (Raluy et al., 2005a).

CML 2 *baseline*	Ecopoints 97	EI 99
Abiotic depletion	NOx	Carcinogens
Global warming	SOx	Respiratory Inorganic
Marine aquatic eco-toxicity	NMVOC [a]	Climate change
Acidification	CO_2	Ecotoxicity
	Waste	Acidification / Eutrophication
	Energy	Fossil fuels

[a] Non-Methane Volatile Organic Compound

The research done by Bonton et al. (2012) might be the only one which has taken into account that the provided raw water and produced drinking water would be of same quality in both the treatment processes (Igos, et al., 2013). Bonton et al. (2012) compared the environmental impacts of an enhanced conventional treatment process and a nanofiltration treatment process, and the modelling were done in SimaPro-software and the applied LCIA-method was Impact 2002+. In addition, the impact of different energy sources were investigated. The enhanced conventional treatment consists coagulation, flocculation, settling, granular filtration, GAC, chlorination, and corrosion control (Figure 9). The nanofiltration treatment consists four process steps: pre-filtration, nanofiltration, chlorination and corrosion control (Figure 9).

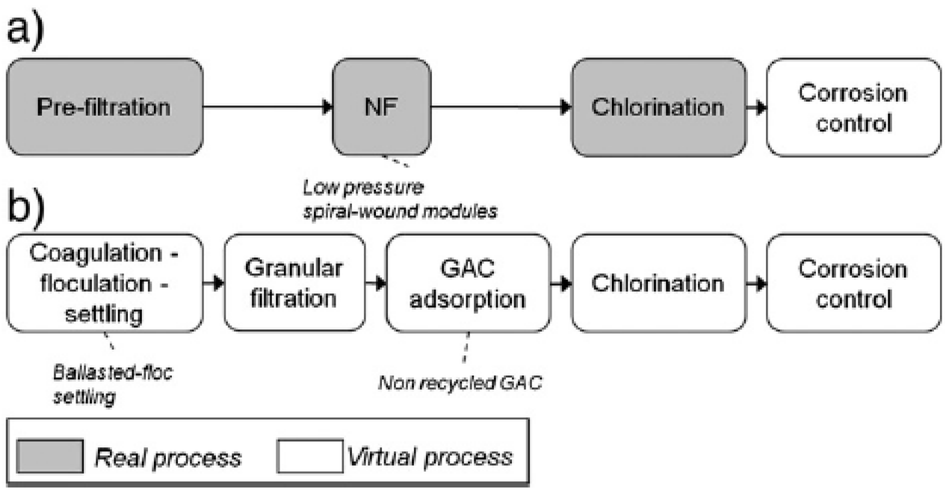


Figure 9. Compared water treatment processes: a) existing nanofiltration plant and b) virtual enhanced conventional process with GAC (Bonton et al., 2012).

The results (Figure 10) showed that the enhanced conventional water treatment process had more impact to the environment than the nanofiltration treatment process. The impacts in the enhanced conventional water treatment process were mainly from the production of GAC and wastewater treatment and disposal. (Bonton et al., 2012.)

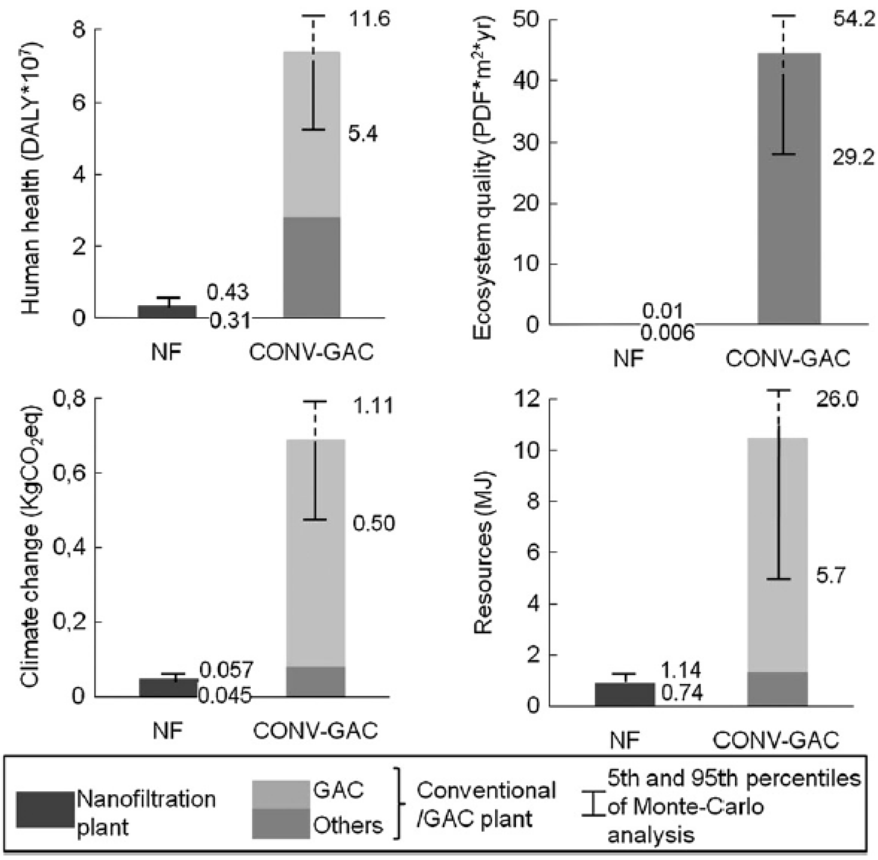


Figure 10. The results of the comparison with IMPACT2002+ method (Bonton et al., 2012).

The impacts from nanofiltration originated from more contributors than in the enhanced conventional treatment: electricity of the operation of the modules, production of chemicals for corrosion control, the production of nanofiltration membranes and transport of materials and chemicals. Another aspect, regarding different life cycle stages, was that the impacts of construction phase were 3-9 times lower than impacts of operation phase in the nanofiltration treatment process. The dominating life cycle stage was the operational phase whereas the decommissioning phase was negligible due to steel recycling. (Bonton et al., 2012.) According to Igos et al. (2014) the ecotoxicity of sludge spreading is overestimated since aluminium is covered as a metal form while the LCIA-method used, Impact2002+, applies to aluminium ion. The chosen mid-point impact categories from Impact 2002+ were human toxicity (carcinogens and non-carcinogens), respiratory inorganics, ionizing radiation, ozone layer depletion, respiratory inorganics, aquatic ecotoxicity, terrestrial ecotoxicity, terrestrial acidification and nitrification, land occupation, aquatic acidification, aquatic eutrophication, global warming, non-renewable energy and mineral extraction. The excluded impact categories were water turbined, water withdrawal and water consumption. (Bonton et al., 2012.)

Vince et al. (2008) conducted the LCA with Gabi-software and the LCIA-method was IMPACT 2002+. The water treatment process included several technologies such as remineralization, clarification, sand filtration, ozonation, GAC filtration, cartridge filters, ultrafiltration and disinfection. The contribution of the different process steps to the environmental impacts are shown in Figure 11. The environmental impacts resulted mostly from coagulant production, lime, soda, and CO_2 production and electricity production for water treatment process. The decommissioning and the impacts of concentrate, membrane cleaning and filter cleaning discharges were excluded. Compared to Bonton et al. (2012) and to Igos et al. (2014), both having the same LCIA-method, the GAC production did not have as much of an environmental impact and remarkably even the construction had more of an impact.

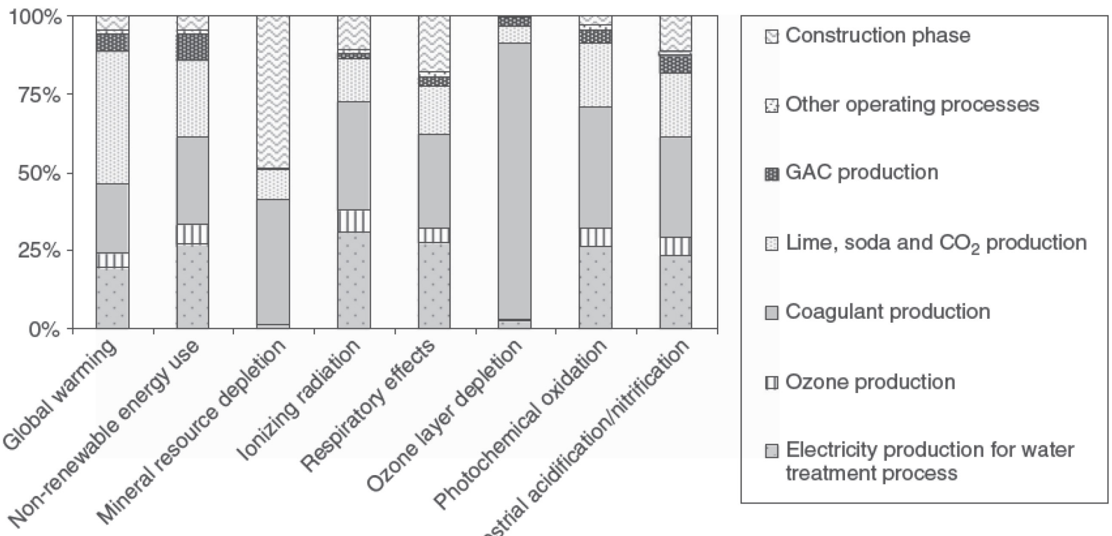


Figure 11. The contribution of process steps to the environmental impacts (Vince et al., 2008).

Barrios et al. (2008) assessed the environmental impacts and financial impact of water treatment process supplied with biological activated carbon filtration (BACF). The operational phase had been accounted and the construction and demolition phases had been excluded. Most of the environmental impacts resulted from softening, coagulation and BACF and the contribution to total environmental impacts was respectively 45.7 %, 23.3 % and 13.6 % of the total environmental impacts. The LCA was done in SimaPro, LCIA method was Eco-Indicator 99 and it was done according to ISO-14040 standard. (Barrios et al., 2008.) When compared to previously mentioned research the impact of the electricity is not shown to be of relevance which clearly differentiates this research from the other ones.

Mohapatra et al. (2002) compared an existing conventional treatment supplied with GAC and an existing treatment integrated with two alternative reverse osmosis treatment processes. The environmental scores were similar and conventional energy, GAC and softening contributed to the environmental impacts altogether with 86-92 % depending on the process. Researchers used Eco-Indicator 95 as and LCIA-method and LCAqua software therefore construction, decommissioning and liquid discharges were excluded.

Raluy et al. (2005b) compared reverse osmosis plant and surface water transfer technology and concluded that desalination was better alternative when considering technological improvements and the cut-offs that had been made. The LCA was done in SimaPro and three different LCIA-methods were used: CML 2 Baseline 2000, Eco-Indicator 99 and Ecopoints 97. The results are shown in Table 6. The operational phase dominated in both alternatives while the domination was significantly higher in desalination process than in water transfer technology. In desalination process the operational phase contributed to 89.05-97.91 %**,** depending on the LCIA-method, to the total environmental scores. The construction phase contributed to 2.03-10.22% to the total environmental scores. In the water transfer technology the operational phase contributed to 66.40-95.50 % to the total environmental scores, depending on the LCIA-method and repayment option, and the construction phase contributed to 4.50-33.60 % to the total environmental scores.

Table 6. The contribution divided between phases and LCIA-methods (Raluy et al., 2005b).

Process	Life cycle phase	Unit	EI 99	Ecopoints 97	CML 2 *baseline*
RO	Assembly	%	6.95	10.22	2.03
	Membranes	%	0.77	0.28	0.06
	Operation	%	92.28	89.05	97.91
	Final disposal	%	0	0	0
ERWT (50 years)	Assembly	%	19.09	20.32	4.50
	Operation	%	80.91	79.68	95.50
ERWT (25 years)	Assembly	%	31.58	33.60	8.58
	Operation	%	68.41	66.40	91.42

However, the results must be evaluated against the cut-offs that had been made. The impact on biodiversity was excluded even though it was likely that the endemic species would have born some consequences. Furthermore, the impact of the extraction of the water resource in the Ebro River basin, impact of concentrate and the water treatment of Ebro River Water Transfer (ERWT) were excluded. (Raluy et al., 2005b.)

As a conclusion the results are affected by the change of the LCIA-methods. The operational phase has been the most dominating phase and the decommissioning phase is negligible. The most dominating activities depend on, among others, the resources used to produce the electricity, type of chemicals, quality of the raw water and chosen LCIA-method. Most valued results are modelled with a midpoint method.

3 Goal Definition and Scope Definition

The goal definition is the first phase in the LCA. The goal definition describes the intended application, method limitations, assumption limitations and impact limitations. Moreover, it introduces the decision-context, the reasons carrying out the study, target audience, whether it includes a comparison, commissioner of the study, and other influential actors. (EC-JRC, 2010a).

The intended application is the comparison of the environmental impacts of two potable water treatment processes of surface water. The processes are enhanced conventional water treatment process in Helsinki and an enhanced membrane treatment process with a loose nanofiltration membranes. This study is a location specific therefore the results are not applicable to any other potable water treatment processes. The LCA-software used was openLCA 1.5.0 and the databases were ELCD 3.2. and Bioenergiedat. The impact assessment method was downloaded from openLCA LCIA methods 1.5.6. The impact coverage is limited. The assumptions and exclusions base on the knowledge of ADWATECH-members. The following assumptions were done: the lifetime of the treatment plant is 30 years, the lifetime of the membrane is 7 years, the lifetime of the pipes, pumps, and valves are 30, the lifetime of actuators and motors are 15 years. The water treatment process is included but raw water extraction, one intermediate pumping, and drinking water distribution are excluded. In addition, the treatment of sludge, membrane concentrate, and membrane cleaning discharge were excluded. The decommissioning phase of the water treatment plant is thought to be negligible therefore decommissioning of most of the materials is excluded with few exceptions. Other exclusions are listed more specifically on the scope definition phase.

The decision-context defines LCI modelling principle and the method approach. The decision context is a micro-level decision support- situation A, meaning that results are not influential in a way that would change the market in the water treatment sector but were to have an impact in a lower decision level, in this case in HSY (Helsinki Region Environmental Services Authority). (EC-JRC, 2010a).The reason for carrying out this research is the high consumption of chemicals in Vanhakaupunki treatment plant. The increase in chemical consumption is due to the increasing amounts of NOM in Lake Päijänne, the source of raw water of Helsinki Capital Region. In addition, the increase in the population increases the consumption of drinking water leading water treatment plant to function near its maximum capacity. As a result, HSY is surveying other possibilities to treat the water and this research is to compare environmental impacts of water treatment processes.

The scope definition further describes the LCA by identifying and describing the product or process in line with the goal definition. The scope definition outlines the type of the deliverable of the LCA, the process and its function, functional unit, and reference flow, and LCI modelling framework and handling of multifunctional processes and products. The scope definition also defines system boundaries, completeness requirements, and related cut-off rules, LCIA impact categories, LCIA method, LCI data quality requirements regarding technological, geographical and time-related representativeness and appropriateness and information on the data e.g sources. (EC-JRC, 2010a).

Next, the deliverable of the LCA, details on the processes, function, functional unit, reference flow, LCI modelling provisions, system boundaries, and cut-off criteria are presented. The deliverable of this study will be used in a comparative LCA study in which a superiority is chosen over another process. The processes are the enhanced conventional water treatment process in Helsinki and a water treatment process with loose nanofiltration membranes. First information on the current water treatment process will be provided and secondly information on the loose nanofiltration membrane process will be provided.

The enhanced conventional treatment process includes the process itself but also the production of limewater produced by HSY (Figure 12). Chemical precipitation is the first process step in which ferric sulfate, $Fe_2(SO_4)_3$, is added to the raw water. After chemical precipitation flocculation phase mixes the water, and settling removes the flocculated mixture from the water. From the settling basins water is led to the filtration consisting of mixed-bed filters containing sand and limestone. From the mixed-bed filters the water flows to the contact basin. After having flowed through the contact basin the water is ozonated and carbon dioxide, CO_2, is added. After ozonation the water flows through the basins which are supplied with GAC. The following process steps are addition of limewater and disinfection with UV-light. In the final process steps sodium hypochlorite (NaClO), ammonia water (NH_3 x H_2O) and carbon dioxide (CO_2) are added to the water. The production of limewater requires burnt lime transported from Lohja, Finland.

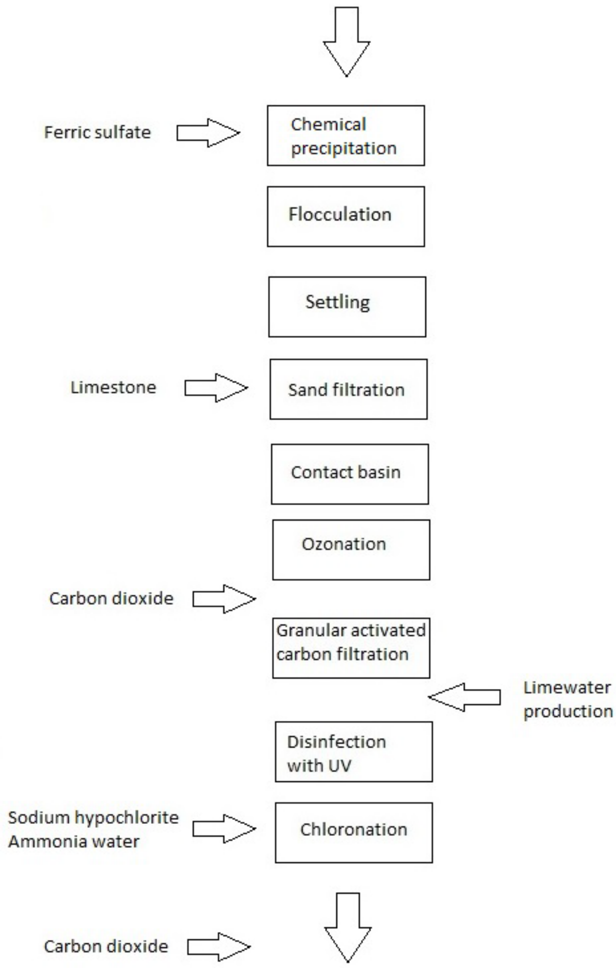


Figure 12. Enhanced conventional water treatment process.

The membrane treatment process includes the process itself but also the production of limewater. The membrane treatment process is based on trials conducted at HSY Pitkäkoski water treatment plant purifying the same raw water as Vanhakaupunki WTP (water treatment plant). The data for manufacturing of membranes is based on Bonton et al. (2012) and measurements of Panu Laurell. The size of the building required for membrane filtration is based on research of Panu Laurell, Gothenburg WTP and Bonton et al. (2012). In the beginning of the membrane treatment process a cartridge filtration filtrates the water. After the cartridge filtration the water is pressurized and pushed through a loose nanofiltration membrane. Sodium hydroxide (NaOH), hydrochloric acid (HCl), Sodium-EDTA and sodium triphosphate (STP) are utilized as periodical cleaning chemicals. The membrane is a polyamide-based membrane that has been modified with piperazine. The molecular weight cut-off is 3.5 kDa. The membrane is housed in an 8” spiral module. During the membrane filtration two constituents are formed: purified water and membrane concentrate. The membrane concentrate is excluded in this research. The water is lead to contact basin after which it is lead to basins supplied with GAC. The following process steps are the addition of limewater and UV-disinfection. In the final process steps sodium hypochlorite (NaClO), ammonia water (NH_3 x H_2O) and carbon dioxide (CO_2) are added to the water. The production of limewater is the same as in the enhanced conventional water treatment process.

The function of the processes is to purify water in such a way that the water quality fulfills the drinking water quality standards of European Union. The minimum legislative requirements are in appendix I&II (EC, 1998). Appendix I presents the microbiological parameters and appendix II presents the chemical parameters. The functional unit is 1 m^3 of water provided for duration of 0.6 s. The capacity of the Vanhakaupunki water treatment process is 52560000 m^3 per year and 1576800000 m^3 in 30 years, which is the assumed lifetime of the plant. Alternative or complementary to the functional unit were not defined since functional unit of 1 m^3 is highly applicable when considering water treatment process and its output. The reference flow is 1 m^3. The function of the treatment process, or rather the minimum legal requirements, are not highly variable.

The LCI modelling provisions presents the guidelines on how to proceed in a given situation and depends on the decision-context. In this research, the decision-context is situation A, which determines the life cycle model to be an attributional model. (EC-JRC, 2010a).
The system boundary diagram of the water treatment processes is in Figure 13. The production stage of the potable water is included. The production stage contains the infrastructure, chemicals, electricity and other materials needed to produce the water. The use stage of the potable water by the consumers is excluded since it is not a matter to be considered according to the goal definition. The waste management of the potable water itself but also the liquid discharges are excluded. The treatment of liquid discharges from the processes are a matter of concern since the quality vary between enhanced conventional and membrane treatment process. The exclusion is discussed in the interpretation. The waste management of parts of the infrastructure is considered, e.g GAC and membranes. Recycling is not considered in the study. The first process step in the current water treatment is production of raw materials and the last process step is decommissioning of GAC. Respectively, for membrane treatment process the first step is production of raw materials and the last step is decommissioning of membranes.

In the scope definition, the system boundaries being set act as a barrier which divide the LCA into technosphere and ecosphere. The ecosphere is the environment and the technosphere is the product system meaning the process under LCA-study. Human influences on materials and products are in the technosphere while in the ecosphere there exists no human influence. The ecosphere contains resources still untouched and finally, the ecosphere is the receiving environment for emissions and deposited goods. The flows in LCA are divided into elementary, product, reference and waste flows. Ideally, only the elementary flows pass the system boundary, from ecosphere to technosphere and from ecosphere to technosphere. In the technosphere the process, in this case potable water treatment processes are divided into sub-processes such as sodium hypochlorite production, transportation of sodium hypochlorite, production of GAC. These sub-processes are based on existing supply chain of the water treatment process.

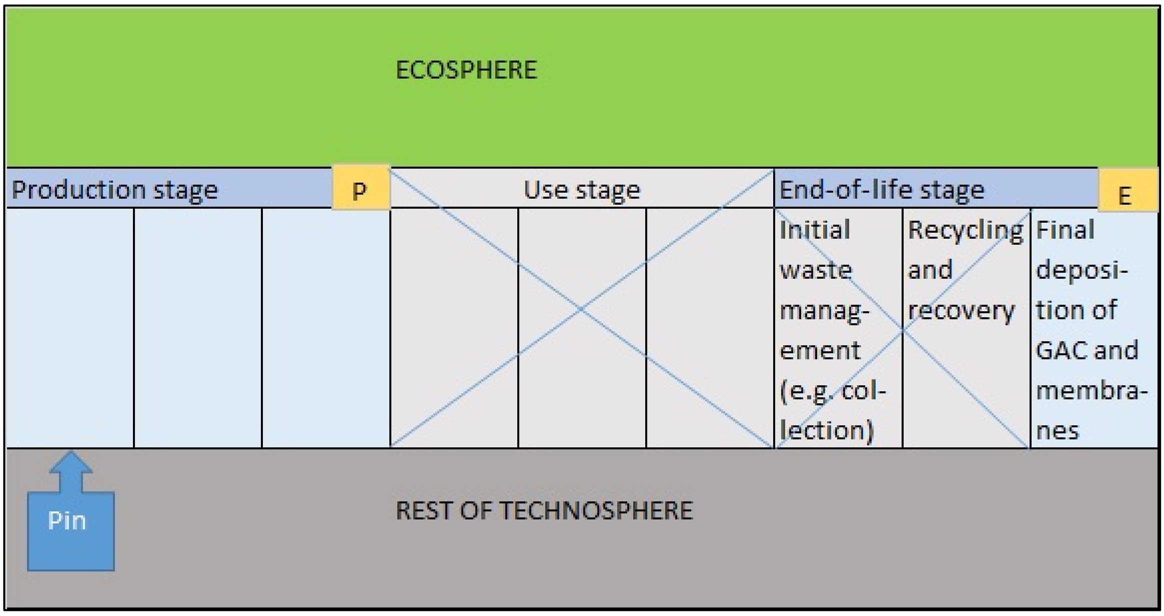


Figure 13. Combined system boundary diagram of the enhanced conventional and membrane treatment process. Production of drinking water is included as a whole of the life cycle stages, the use stage is excluded and end-of-life stage is included partly. The end-of-life treatment of GAC and membranes is included and the end-of-life treatment of the potable water, namely wastewater treatment is excluded.

The exclusions of the study: raw water and drinking water distribution, treatment of sludge, treatment of membrane concentrate, and membrane cleaning discharge, solar power of the water treatment plant, office and laboratory parts, foundations of infrastructure, a pumping stage of contact basin, repair, maintenance processes, heating of the plant, and end-of-life treatment (except for granular activated carbon and membranes). The environmental impact of the end-of-life treatment of some substances is insignificant therefore we have concentrated on the most relevant substances that do have environmental impact when they are disposed such as GAC and membranes.

The definition for cut-off criteria is defined after life cycle impact assessment (EC-JRC, 2010a). The quantitative cut-off criteria is 2 %. The cut-off criteria excludes the processes contributing to the results less than with 2 %. After determining the cut-off, the impact of the included processes are summed. The summed impact states the impact coverage of impact category. The impact coverage is in Table 7.

Table 7. Impact categories of ReCiPe (H) Midpoint and the impact coverage of the impact categories.

Impact category	*Impact coverage*
Agricultural land occupation	100 %
Climate change	94 %
Fossil depletion	93 %
Freshwater ecotoxicity	95 %
Freshwater eutrophication	100 %
Human toxicity	92 %
Ionizing radiation	98 %
Marine ecotoxicity	94 %
Marine eutrophication	98 %
Metal depletion	90 %
Ozone depletion	95 %
Particulate matter formation	92 %
Photochemical oxidant formation	91 %
Terrestrial acidification	93 %
Terrestrial ecotoxicity	93 %
Urban land occupation	100 %
Water depletion	100 %
Natural land transformation	-100 %

The chosen LCIA-method is ReCiPe 2008 midpoint (H) hierarchial. Although ILCD Guide suggests covering certain impact categories by default on midpoint level, it is acknowledged that Recipe does not include impact categories such as acidification of water, eutrophication of land and depletion of renewable energy resources. The appropriate methods to choose from were Recipe and CML. In 7.9.2017 Recipe midpoint (H) is chosen. Since endpoint modelling has its uncertainties the midpoint is chosen. Normalization and weighting is not included. Exclusion of normalization was decided in August 2017.

4 Life Cycle Inventory Analysis

The water treatment process is divided into foreground and background systems (Figure 14). Foreground system consists processes that are specific to the water treatment plant or processes provided by one supplier. Background system consists processes where average data would represent the process more accurately. (EC-JRC, 2010a). Foreground system consist sodium hypochlorite, ferric sulfate, raw water, and infrastructure. Background system consists ammonia water, limestone, GAC, carbon dioxide, oxygen, hydropower of the plant, wind power of the plant, and bio-energy from municipal solid waste of the plant There is two processes that could belong to either of the systems or both: production of limewater and bio-energy of the plant. The production of limewater could belong to background system since the production of burnt lime would be representative with average data. However, production of limewater occurs in the water treatment plant consuming specific kind of biogas. Harnessing biogas from digested wastewater sludge and biogas from industrial bio waste might lead the production of limewater to belong in foreground system. The electricity of the plant consist on bio energy, hydro energy, and wind energy. The representativeness of average data in the bio-energy production from digested wastewater sludge and industrial bio waste should be further evaluated.

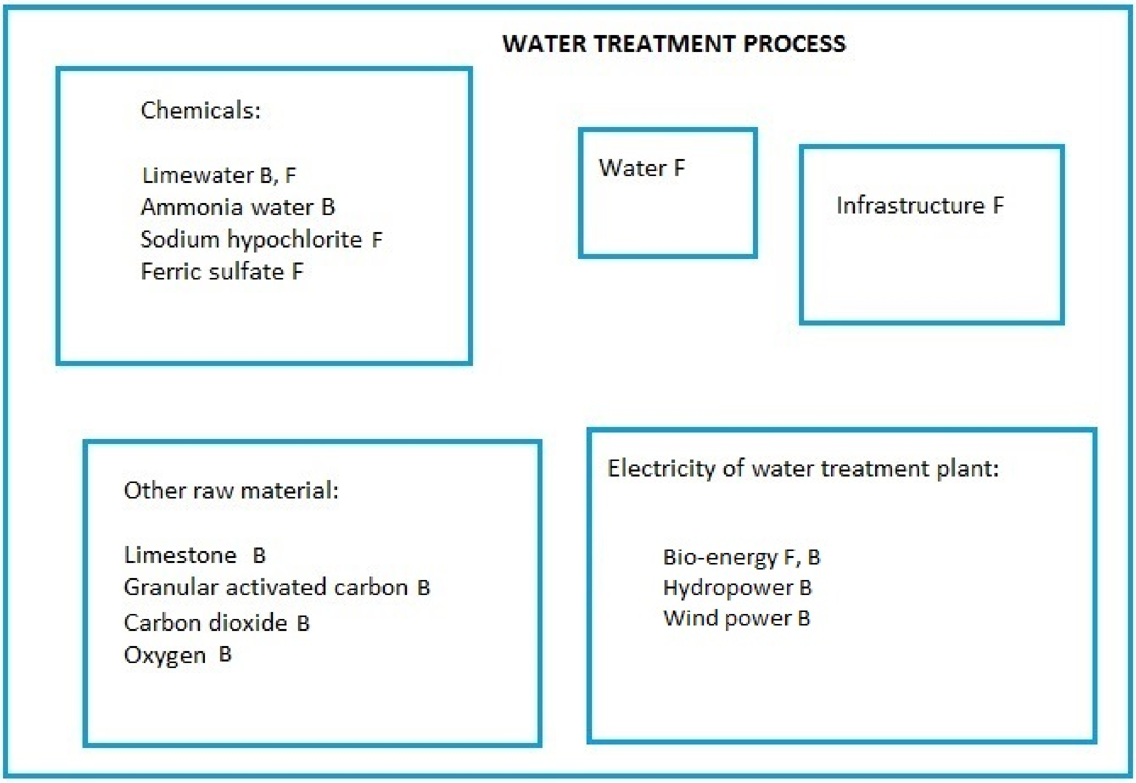


Figure 14. Water treatment process divided to background system (B) and foreground system (F).

The water treatment plant consists on processes created and processes already existing in ELCD and Bioenergiedat databases. The unit processes created for the study are in the Figure 15. First column, transportation of elements of infrastructure, consist on processes existing in the databases and study-specific transportation. In the second column, production of burnt lime, ferric sulfate, sodium hypochlorite, GAC, and ammonia water present created unit processes.

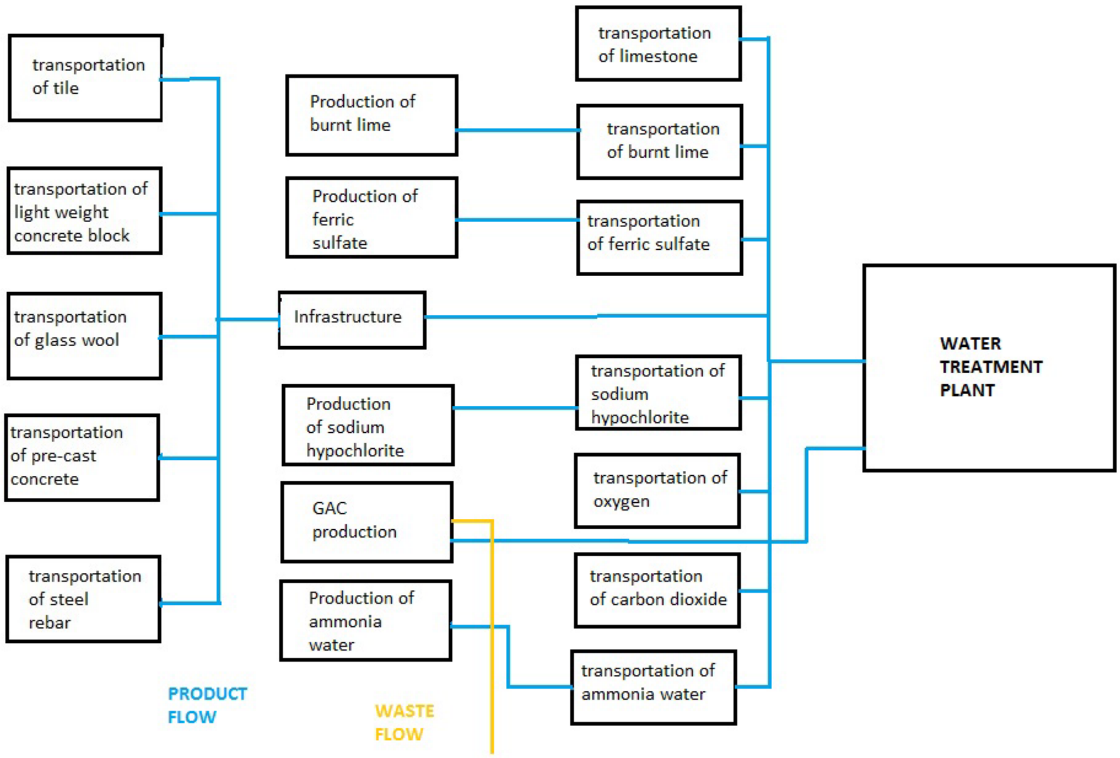


Figure 15. Created unit processes. Blue line indicates product flow between the processes and yellow line is waste flow. First processes on the right present transportation of elements for the infrastructure.

4.1 Electricity

The electricity consumption of treatment plant consist not only the electricity consumption of the water treatment process but also electricity consumption of limewater production. Heating of the plant is not included since district heating is applied. Limewater production is presented later in the chapter. Most of the data for the electricity of Vanhakaupunki treatment process is taken from a time period starting from December 2016 to March 2017 and the data were given by HSY (Poutanen, 2017a). This period is chosen since operational changes took place in December, therefore longer time period would result in an unrepresentative operation of the treatment process. However, the correlation of intermediate and high-pressure pumping is from April 2017 because new pumps were installed. The electricity for the treatment process is calculated based on the following equation:

E = treatment plant – high pressure pumping − intermediate pumping − reserve power

The share of different electricity sources is bio-energy 89.1 %, wind power 9.0 %, hydro power 1.8 % and solar power 0.1% of the total electricity consumption (Kettunen, 2017). The origin of electricity, and the amount of electricity are shown in Table 8. The share of electricity consumption is based on the electricity use in 2016. Solar power is excluded.

Table 8. The sources of electricity in Vanhakaupunki water treatment process.

	% of total	*[kJ/m3]*
Solar power	0.1	27
Wind power	9	24
Hydropower	1.8	49
Bio energy (of which)	89.1	240
Methane	57	140
Biogas from biowaste	10	25
Biogas from sludge digestion	32	78

Most of the electricity bases on the electricity from landfill gas utilisation which provides 51 % of the total electricity. The provider for the process in OpenLCA supports the technology of landfill gas utilisation well. The provider for the second biggest energy source, biogas from digestion of sludge of wastewater treatment process, is not as representative. In the provider, the sludge is fermented by burning with a biogas motor and spread to the fields, while in HSY the sludge from wastewater is digested followed by compostion. Both, the electricity from wind power and the biogas from bio waste provides 9 % of the total energy consumption. Both processes are thought to be quite representative. The least amount of electricity, 2%, is provided by hydropower technology and the provider is representative.

4.2 Chemicals

4.2.1 Ferric Sulfate

The data for ferric sulfate consumption, $Fe_2(SO_4)_3$, were collected from HSY (Poutanen, 2017b) and Kemira (Hesampour & Kettunen, 2017). The amount of ferric sulfate is calculated based on an average from the years 2010-2015 multiplied by 30 years. The increase in chemical consumption during 30 years has been omitted from the calculations. Ferric sulphate data was acquired through a study done by InCopa association (Homa & Hoffman, 2014), which represents the coagulant producers in Europe. Their data is based on values reported by manufacturers on their coagulant production.

The resources spent in producing 1 kg of ferric sulfate are seen in Figure 16. Producing 1 kg of ferric sulfate is mostly impacted by transportation with ship and truck, other significant factors are energy (both natural gas and electricity are utilized) and sulphuric acid. In Figure 16, the number in the bottom left corner of each box indicates the CO_2-equivalents in kilograms formed per kilogram of product and the percent indicates the overall contribution when compared to the total emissions. Moreover the thicker the line the more the process forms CO_2 –equivalents. The inventory data of ferric sulfate is in Appendix III. Ferric sulfate data in the study is generic/average data and is representative. Sulphuric acid is modelled as production residue from another process.

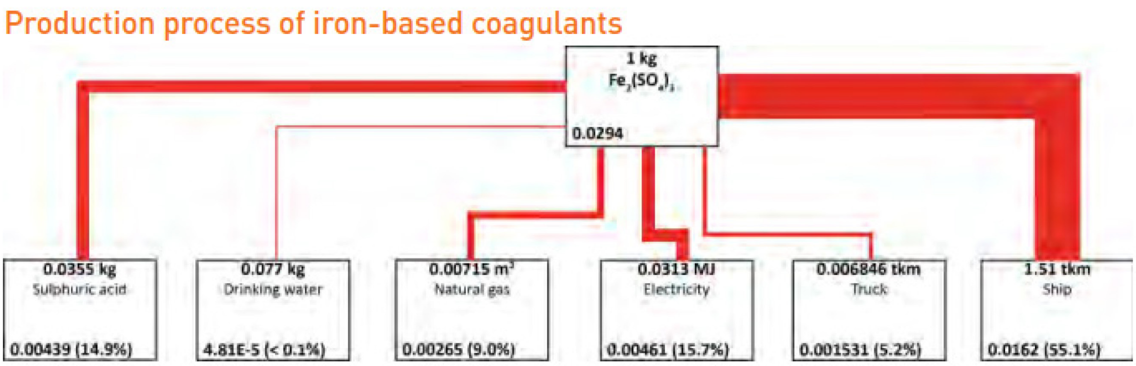


Figure 16. Materials and processes spent in the production of $Fe_2(SO_4)_3$ (Homa & Hoffman, 2014).

4.2.2 Ammonia Water

The inventory of ammonia water consists of data from HSY (Poutanen, 2017b) and Yara (Ylisuutari, 2017). HSY provided the amount of the ammonia water during 2015 and 2016, and average of those years were multiplied by 30. The increase in chemical consumption during 30 years has been omitted from the calculations. Production of ammonia water consumes nitrogen, electricity, and natural gas. The transportation of ammonia water is included in the study. The inventory data of ammonia water is in Appendix III. The values of the raw materials and resources are confidential. The data is representative.

4.2.3 Sodium Hypochlorite

The inventory of sodium hypochlorite consists data from HSY (Poutanen, 2017b), Kemira (Hesampour & Kettunen, 2017) and Meier (1997). HSY provided the amount of the sodium hypochlorite during 2015 and 2016, and average of those years were multiplied by 30. The increase in chemical consumption during 30 years has been omitted from the calculations. Kemira provided information on the resources and raw materials in the production of sodium hypochlorite. Production of sodium hypochlorite consumes salt, energy, steam and water (Hesampour & Kettunen, 2017). The resources for production of steam are shown in Table 9. The values for the table originate mostly from Meier (1997) but there is contributions from other authors as well (Table 9). The transportation of sodium hypochlorite is included in the study. The inventory data of sodium hypochlorite is in Appendix III. The values of the raw materials and resources are confidential. The data quality is quite representative, although the division of steam to sub-processes according to Meier (1997) has not been confirmed from the representativeness of Kemira.

Table 9. Materials and processes for the production of steam (Meier 1997, p.243).

Materials and processes	***Amount per ton of steam***	***Comments***
Natural gas (Nm^3)	97.5	(Bayer et al., 2005), (Frischknecht et al., 1996), (Meier, 1997)
Furnace oil (extra light) (kg)	7.3	(Meier, 1997), (Frischknecht et al., 1996)
Electricity UCPTE (medium voltage) (kWh)	2.8	(Meier, 1997), (Frischknecht et al., 1996)
Deionised water (kg)	1000	(Meier, 1997), (Bretz et al., 1994)

4.2.4 Limewater

The sources for the inventory data originates from HSY (Poutanen, 2017b), Nordkalk (Rannali, 2017) and environmental permit application of Nordkalk (Pöyry, 2016). The water treatment plant produces limewater from burnt lime. Resources for limewater production consist limestone mining in Norway, burnt lime production in Lohja, Finland, transportation and electricity use in the plant. The limestone is from Verdal, Norway. After the mining of limestone, it is transported to Lohja, Finland. After transportation, limestone is transformed to burnt lime. Amount of burnt lime bases on the consumption in January and February 2017 in the plant. As the amount of burnt lime is known, the amount of limestone was calculated stoichiometrically from the following equation:

$$CaCO_3 \rightarrow CaO + CO_2.$$

Significant problems arose in the representativeness of limewater production. The inventory data of the production of burnt lime from limestone was roughly estimated. The data originates from the environmental permit application of Nordkalk (Nordkalk Oy AB, 2016). The production of burnt lime is a multifunctional process but it has not been modelled as a multifunctional process. The environmental permit application did not concentrate solely on the production of burnt lime, and using environmental permit application as a source lead in making significant simplifications. Currently the production of burnt lime, CaO, is estimated to require resources such as limestone, coal, electricity and heavy fuel oil. Basing on generic or average data, the production of burnt lime would be more representative. Even though burnt lime production is rather unrepresentative, omitting it would have been unjustifiable.

The production of limewater from burnt lime requires mostly electricity in the water treatment plant. The electricity consumption is included in the electricity consumption of the treatment plant (Table 8). The transportation is included in the study. The transportation consists ship transportation from Norway to Finland and lorry transportation in Finland. Appendix III presents the inventory data of limewater.

4.3 Other raw material

4.3.1 Limestone

The water treatment plant consumes limestone in the sand filtration. The data for limestone, $CaCO_3$, were collected from HSY (Poutanen, 2017b) and Nordkalk (Rannali, 2017). The calculation was based on the amount consumed in January and February 2017 multiplied by 180. The product name of the limestone is Nordkalk Parfill 1500. The origin of the limestone is from a mine located in Parainen, Finland, from where it is transported to Vanhakaupunki. Transportation of limestone is included in the study. Appendix IV presents the inventory data of limestone.

4.3.2 Granulated Activated Carbon

The water treatment plant consumes GAC in the GAC filtration basins. The information is from HSY (Poutanen, 2017b) and other sources to be mentioned later. The regeneration of GAC takes place in Antwerpen, Belgium and the supplier is Chemviron Carbon. The amount of GAC bases on the volume of basins of activated carbon filtration. The density of the GAC is the bulk density 0.4 kg/m^3. GAC consumes resources in production and regeneration phase. After calculating the amount, the production of GAC and regeneration of GAC during 30 years period were calculated. During 30 years, GAC is regenerated 7.5 times. The regeneration of GAC is four times after which it is disposed (Meier, 1997). The life cycle of activated carbon consists production, four regenerations and disposal. The loss of activated carbon during regeneration is 30 % and it is disposed (Poutanen, 2017b).

The needed materials and processes for the production of activated carbon are crude coal, transportation, electricity, hydrochloric acid, steam and natural gas (Table 10). The production of activated carbon implies production of virgin activated carbon. The values for the table originate mostly from Meier (1997) but the contributions of other authors are seen in Table 10 . The contribution of natural gas originates from Bayer et al. (2005).

Table 10. Materials and processes for the production of activated carbon (Bayer et al., 2005 adapted from Meier, 1997).

Concept	*Materials and processes*	*Amount per kg GAC*	*References*
Raw material	Crude coal (kg)	2	(Meier, 1997), (Bayer et al., 2005) Coal data from (Frischknecht et al., 1996)
Transport (28 t) from mine to activation plant	Transport by truck (kg*km)	600	(Frischknecht et al., 1996)
Mixing, crushing, kiln, drive	Electricity (kWh)	0.021	Electricity data from (Frischknecht et al., 1996); Mixing of coal, Klin drive (Esch et al., 1973); Crushing of coal (Ciba, 1995)
Washing of calcium carbonate	Hydrochloric acid (kg)	0.04	(Meier, 1997); HCl data from (Frischknecht et al., 1996)
Activation	Steam (kg)	3	(Meier, 1997)
Heating (1000 °C, 10 hours	Natural gas (Nm^3)	4.9	Bayer et al. 2005 adapted from ((Meier, 1997) and (Frischknecht et al., 1996)

The materials and processes used in the regeneration of activated carbon are crude coal, steam, natural gas, electricity, and activated carbon for the replacement of loss during the regeneration (Table 11). There is no transport of crude coal nor the use of hydrochloric acid unlike in the production of virgin activated carbon.

Table 11. Materials and processes needed for the thermal regeneration of activated carbon (Bayer et al., 2005 adapted from Meier, 1997).

Materials and processes	*Amount per kg GAC*	*References*
Crude coal (kg)	0.1	(Meier, 1997), (Bayer et al., 2005) Coal data from (Frischknecht et al., 1996)
Electricity UCPTE (medium voltage) (kWh)	0.001	Electricity data from (Frischknecht et al., 1996); Mixing of coal, Klin drive (Esch et al., 1973)
Steam (kg)	0.3	(Meier, 1997), (Frischknecht et al., 1996), (Bayer et al., 2005), (Bretz et al., 1994)
Natural gas (Nm^3)	2.7	(Bayer et al., 2005), (Meier, 1997), (Frischknecht et al., 1996)
Activated carbon (kg):	0.1	For replacement of loss of activated carbon during reactivation. (Meier, 1997)

The steam in the production and regeneration of GAC is further distributed to resources as in Table 9. The production of steam consumes natural gas, furnace oil, electricity, and deionised water.

The data for production and regeneration is representative and of good quality. The disposal of the GAC is excluded since there is no process for disposal of GAC. The impact of exclusion is discussed later. The inventory data of GAC is in Appendix IV.

4.3.3 Ozone and Carbon Dioxide

The production of ozone consists of production of oxygen and transportation of oxygen to the plant. Production of ozone takes place at the plant. The amount of oxygen bases on the amount used during January and February 2017 in the plant (Poutanen, 2017b). The oxygen is transported from Turku to Helsinki. The inventory data of ozone production is in Appendix IV.

The production of carbon dioxide consist of resource of carbon dioxide and transportation of carbon dioxide to the plant (Poutanen, 2017b). The amount of CO_2 bases on the amount used during January and February 2017 in the plant. Carbon dioxide is modelled as a resource, not provided by any process. The oxygen is transported from Porvoo to Helsinki. The inventory data of ozone production is in Appendix IV.

4.4 Infrastructure

Infrastructure bases on the construction and architectural drawings of the water treatment plant. Infrastructure includes the sub-processes in the plant, pipings, and production of lime-water. Sub-processes are for example settling, sand filtration, and ozonation. The inventory data of infrastructure is in Appendix V and the transportation of infrastructure is in Appendix VI. Transportation of highest amount of materials were calculated. These materials were glass wool, light weight concrete block, pre-cast concrete, transportation of steel rebar, and tile. Production of tile was modelled as production of light weight concrete block in OpenLCA. Both materials constitute same raw materials but there might be some differences in the production. However, exclusion of tile might have been more unrepresentative. There is a reasonable assumption of infrastructure being insignificant compared to operation, therefore infrastructure is very representative.

5 Life Cycle Impact Assessment

5.1 The Environmental Impacts of Operation and Infrastructure

The results from OpenLCA are in Appendix VIII- XXIV. This chapter presents further analyzed results.

Figure 17 shows the environmental impacts resulting from the infrastructure and operation. The operation clearly dominates the environmental impacts. Infrastructure produces impacts in the impact categories of metal depletion and human toxicity. The depletion of metal is the only impact category in which infrastructure creates more impacts than the operation.

10-20 % amount of environmental impact from the infrastructure occurs in the impact categories ozone depletion, freshwater ecotoxicity, human toxicity, ionizing radiation, marine ecotoxicity, metal depletion, and terrestrial ecotoxicity. The impact category natural land transformation is omitted since the result was -100 % from the production of burnt lime.

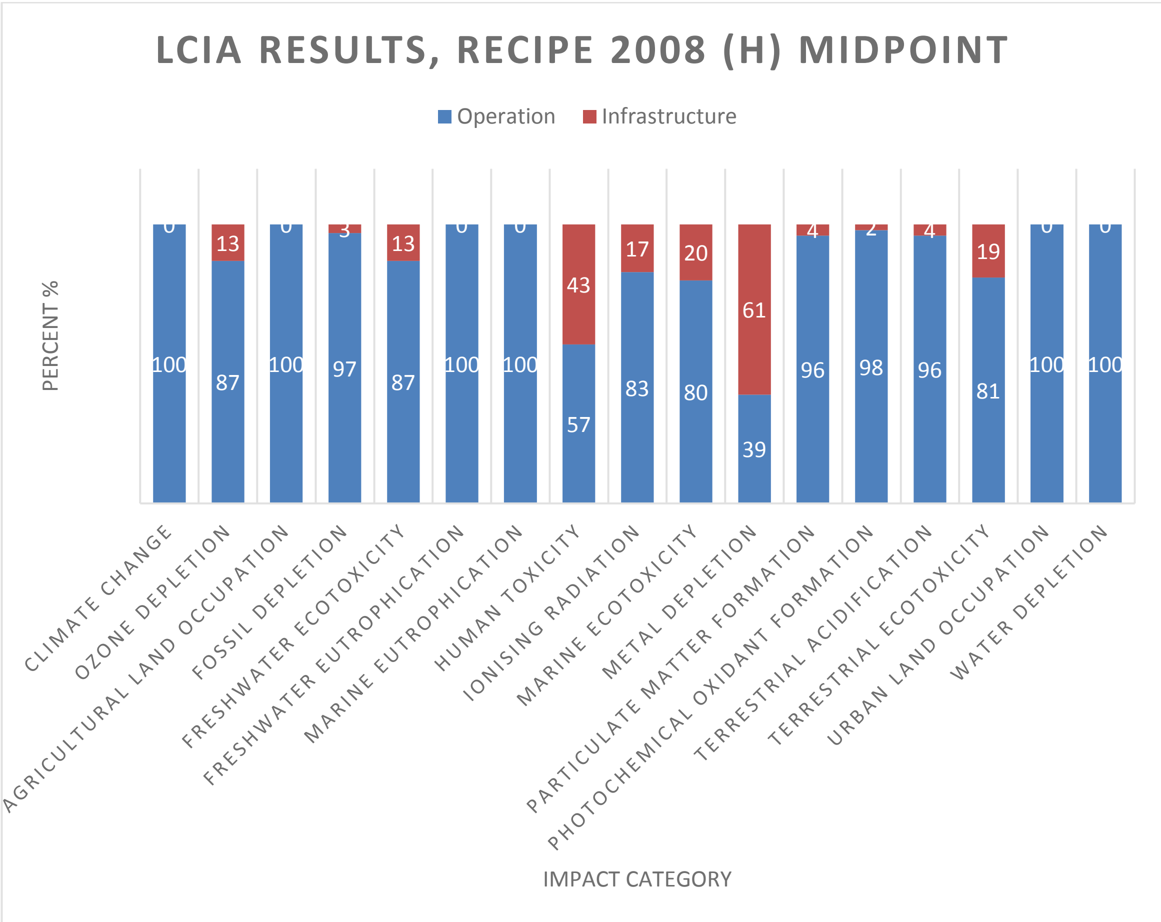


Figure 17. LCIA results: comparison of the environmental impacts between operation and infrastructure.

Figure 18 presents the share of impact from chemicals, electricity consumption of the plant, oxygen, and infrastructure. Impact categories natural land transformation and water depletion are excluded. The depletion of water results from the functioning of water treatment plant. The use of water resources origins to Lake Päijänne. Since water resources are sufficient in Finland, the relevance of this impact category is questionable. The electricity consumption of the plant (biogas) produces most of the environmental impacts. The chemicals produce all the environmental impacts in agricultural land occupation and urban land occupation. The relevance of these impact categories in Finland might be questionable since the populated area is low compared to unhabitable area.

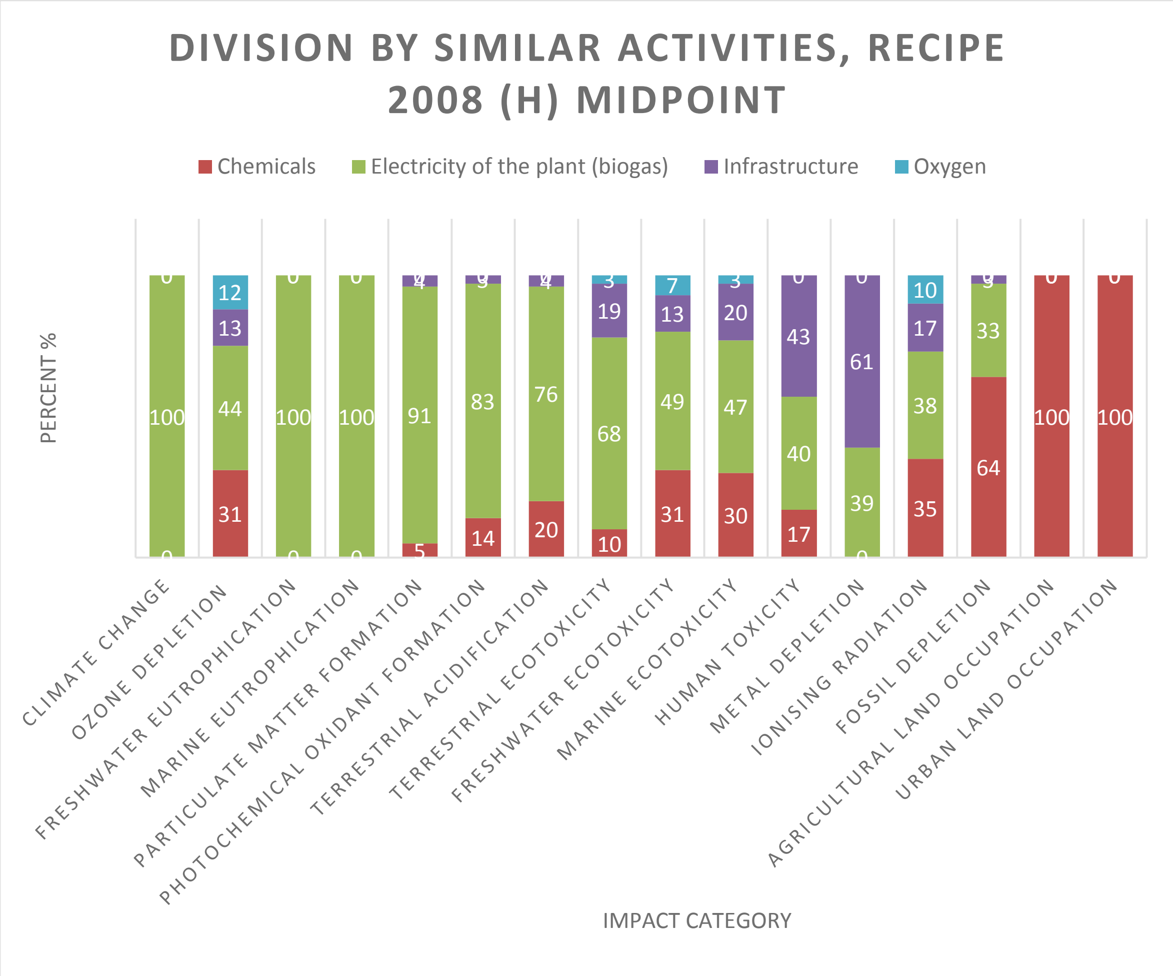


Figure 18. LCIA results distributed to impacts from chemicals, electricity consumption of the plant, oxygen, and infrastructure.

The detailed information on the environmental impacts per impact category is in Appendices XXV-XL. Overall, the electricity consumption is higher as Figure 18 might suggest since the impact from chemicals is partly due to the overall electricity consumption.

Most of the impacts are due to electricity consumption of water treatment plant. In addition, production of burnt lime (for limewater), ammonia water and sodium hypochlorite create the environmental impacts. In reality, the production of limewater creates bigger share of impacts since the electricity consumption of the production is included in the electricity consumption in the water treatment plant. Hard coal produces the impacts in the production of burnt lime. Natural gas and electricity consumption produce the impacts in the production of ammonia water and sodium hypochlorite. The impact from infrastructure would be reduced if recycling had been accounted.

5.2 Sensitivity Analysis

LCIA calculation with CML Baseline presents the uncertainty of the results. CML Baseline was chosen since it would have been the other possible LCIA method. CML Baseline is missing impact categories agricultural land occupation, ionizing radiation, particulate matter formation, urban land occupation, natural land transformation, and water depletion all of which are in ReCiPe 2008 (H) midpoint. The relevance of these impact categories is discussed later. Compared to ReCiPe, the impacts are more determined by operation. Operational influence increased in metal depletion, human toxicity and terrestrial ecotoxicity.

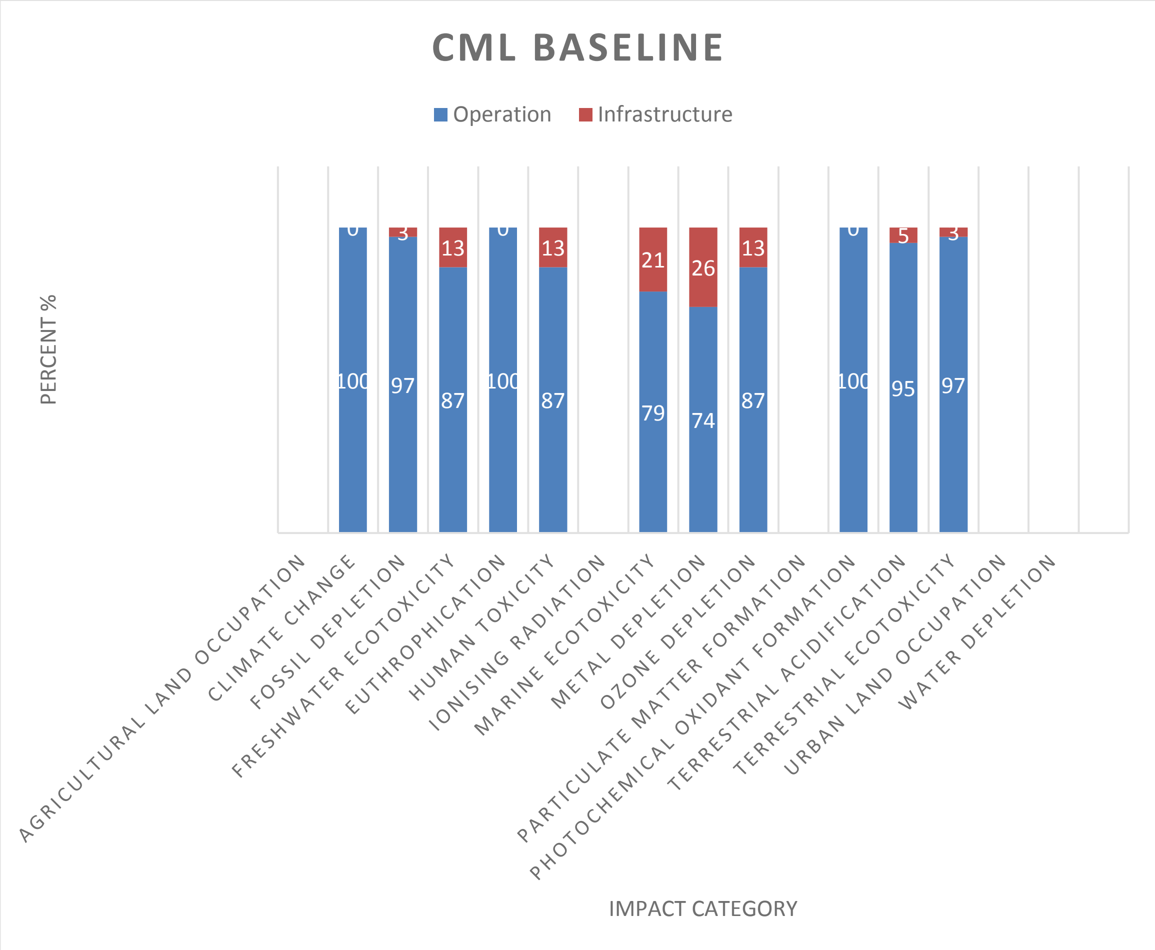


Figure 19. LCIA results: comparison of the environmental impacts between operation and infrastructure.

Table 12 presents the contribution of different activities with ReCiPe (H) Midpoint and CML-baseline. Green color indicates no difference in the results, e.g. no sensitivity, and red color indicates some sensitivity. From Table 12 one may see that the impacts are the same in climate change, fossil depletion, freshwater eutrophication, and ozone depletion. There is no sensitivity in these categories between CML-baseline and Recipe (H) Midpoint. The reason for identical results in these impact categories is due to the fact that ReCiPe partly bases on CML. The impact categories freshwater ecotoxicity, human toxicity, marine ecotoxicity, metal depletion, photochemical oxidant formation, terrestrial acidification, marine eutrophication and terrestrial ecotoxicity are sensitive to change of the method. Even though marine eutrophication seems to be the same according to the table, Appendix XLI presents marine eutrophication to have differences in the impacts with each method.

Table 12. The contribution of different activities with ReCiPe (H) Midpoint and CML baseline. Columns are divided to chemicals, electricity of the plant from biogas, electricity of the plant from wind power, infrastructure and oxygen. CML-baseline is missing impact categories agricultural land occupation, ionizing radiation, and urban land occupation.

Impact category	Recipe Chemicals	CML Chemicals	Recipe Electricity	CML Electricity	CML Wind pow	Recipe Infrastruct	CML Infrastruct	Recipe Oxygen	CML Oxygen
Agricultural land occupation	100		0			0		0	
Climate change	0	0	100	100	0	0	0	0	0
Fossil depletion	64	64	33	33	0	3	3	0	0
Freshwater ecotoxicity	**31**	**19**	**49**	**65**	0	13	13	**7**	**3**
Marine eutrophication	**0**	**0**	**100**	**100**	**0**	**0**	**0**	**0**	**0**
Freshwater euthrophication	0	0	100	100	0	0	0	0	0
Human toxicity	**17**	**21**	**40**	**60**	**0**	**43**	**13**	**0**	**6**
Ionising radiation	35		38			17		10	
Marine ecotoxicity	**30**	**8**	**47**	**61**	**0**	**20**	**22**	**3**	**9**
Metal depletion	**0**	**57**	**39**	**15**	**2**	**61**	**26**	0	0
Ozone depletion	31	31	44	44	0	13	13	12	12
Particulate matter formation	5		91			4		0	
Photochemical oxidant formati	**14**	**6**	**83**	**94**	**0**	**3**	**0**	0	0
Terrestrial acidification	**20**	**21**	**76**	**71**	**0**	**4**	**5**	**0**	**3**
Terrestrial ecotoxicity	**10**	**3**	**68**	**94**	**0**	**19**	**3**	**3**	**0**
Urban land occupation	100		0			0		0	
Numbers are percents from total environmental impact									

Figure 20 presents the sensitivity analysis based on change of LCIA method to CML-baseline. Sensitivity analysis presents the difference between the methods overlooking the sign. The most sensitive impact category is metal depletion in which the difference of chemical contribution is significant with 57 percents. This means that changing a method to CML-baseline, the impact of chemicals increased from 0% to 57 %. Impact categories of ecotoxicity (terrestrial, marine and freshwater) and human toxicity are less sensitive to the method change. The least sensitive impact categories, of the impact categories that changed in CML-baseline, are photochemical oxidant formation and terrestrial acidification.

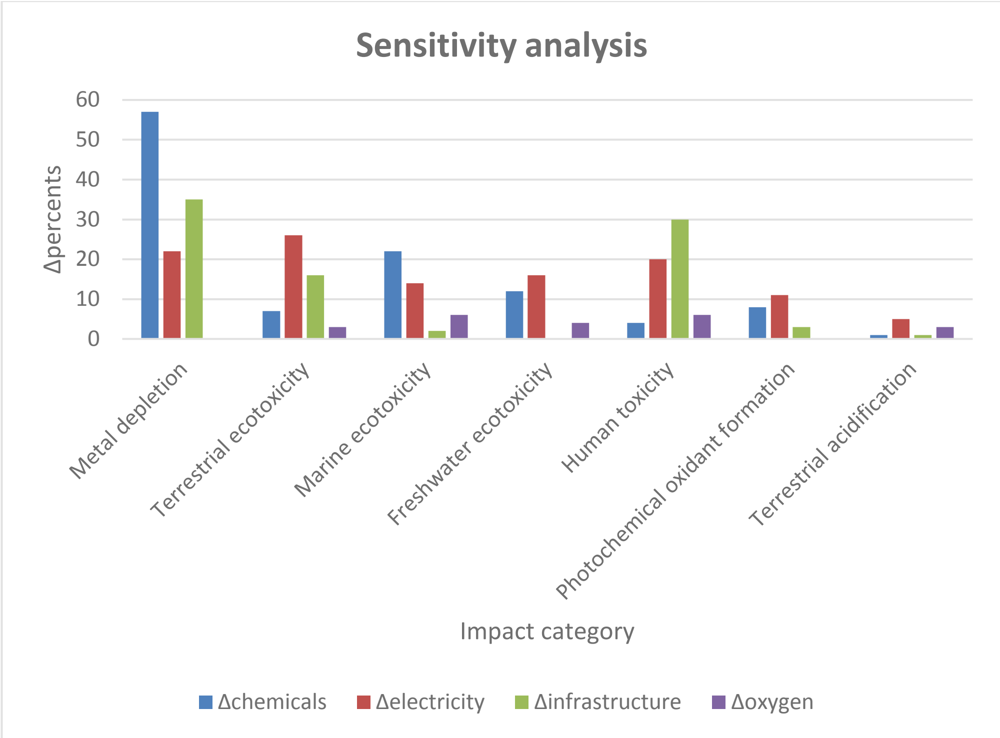


Figure 20. The sensitivity analysis of enhanced conventional water plant.

6 Conclusion

According to the results, the dominance of operation over infrastructure occurred in the environmental impacts and it corresponds well with other literature. This applied for both methods, ReCiPe (H) Midpoint and CML-Baseline. The environmental impacts from the operation resulted from the electricity consumption of the water treatment plant and production of chemicals, sodium hypochlorite, limewater and ammonia water. The environmental impacts of the chemicals resulted from the use of natural gas, electricity and hard coal. Production of ferric sulfate caused negligible environmental impacts compared to other chemicals, which might rely partly on one raw material, sulfuric acid, being a by-product from another process.

The insignificance of the production GAC was unexpected. However, the contribution of production of GAC does vary according to the literature. The production of GAC in Igos et al. (2014) and Bonton et al. (2012) has significantly higher impact. The difference in the impact of GAC production might depend on the regeneration interval, poor raw water quality and simplicity of the water treatment process. Another aspect worth mentioning is that in Igos et al (2014) weighting is applied which makes the comparison difficult.

Unfortunately, the uncertainties in the data of burnt lime decreased the overall quality of the data. Better quality inventory data should be gained and multifunctionality solved. In addition, since limewater production from burnt lime is included to the electricity consumption of the water treatment plant, a higher impact from limewater production is expected.

There is some issues related to impact categories that should be mentioned. Some of the impact categories could be excluded based on their irrrelevance for finnish surroundings. This might apply to agricultural land demand, urban land use, water depletion, and natural land transformation. Excluded impact categories were acidification of water, eutrophication of land and depletion of renewable energy resources. As Finland has acidic surroundings, impact category for freshwater acidification would be highly justifiable. Use of country-specific characterization factors might be reasonable in the acidification.

7 References

Antikainen, R., 2010. *Elinkaarimetodiikkojen nykytila, hyvät käytännöt ja kehitystarpeet,* s.l.: Suomen Ympäristökeskus.

Antikainen, R., 2012. *Elinkaarimenetelmät yrityksen päätöksenteon tukena,* s.l.: Suomen Ympäristökeskus.

Barrios, R. et al., 2008. Environmental and financial life cycle impact assessment of drinking water production at Waternet. *Journal of Cleaner Production,* Volume 16, pp. 471-476.

Bayer, P., Heuer, E., Karl, U. & Finkel, M., 2005. Economical and ecological comparison of granular activated carbon (GAC) adsorber refill strategies. *Water Research,* Osa/vuosikerta 39, pp. 1719-1728.

Bonton, A., Bouchard, C., Barbeau, B. & Jedrzejak, S., 2012. Comparative life cycle assessment of water treatment plants. *Desalination,* Volume 284, pp. 42-54.

Bretz, R., Foery, M. & Fankhauser, P., 1994. *ECOSYS: Integrating LCA into the Corporate Informations Systems: Life cycle assessment: Make it relevant,* Brussels: European Chemical News.

Ciba, 1995. *Energiebedarfstabellen;,* Basel: Ciba-Geigy AG.

De Vries, W., Reinds, GJ., Van Dobben, H., De Zwart, D., Aamlid, D., Neville, P., Posch, M., Auée, J., Voogd, J.C.H. & Velet, E.M. 2002. Intensive Monitoring of Forest Ecosystems in Europe. Technical Report 2002; EC, UN/ECE: Brussels, Geneva.

EC, 1998. *Council Directive on the Quality of Water Intended for Human Consumption,* s.l.: European Union.

EC-JRC, 2010a. *ILCD Handbook. General guide for Life Cycle Assessment: Detailed guidance. 1nd* ed. Luxembourg: European Union. 417 p. ISBN 978-92-79-19092-6.

EC-JRC, 2010b. *ILCD Handbook. Framework and requirements for Life Cycle Impact Assessment models and indicators. 1nd ed.* Luxembourg: European Union. 116 p. ISBN 978-92-79-17539-8

EC-JRC, 2010c. *ILCD Handbook. Analysis of existing Environmental Impact Assessment methodologies for use in Life Cycle Assessment. 1nd ed.* Ispra, Italy: European Union. 115 p.

EC-JRC, 2011. *ILCD Handbook. Recommendations for Life Cycle Impact Assessment in the European context- based on existing environmental impact assessment models and factors. 1nd ed.* Luxembourg: European Union. 159 p. ISBN 978-92-79-17451-3

Esch, U., König, H. & Uhl, L., 1973. *Ullmann's Encyklopedia der chemischen Industrie.* 3 toim. Weinheim: VCH Verlagsgemeinschaft.

Finnveden, G. ym., 2009. Recent developments in Life Cycle Assessment. *Journal of Environmental Management,* Osa/vuosikerta 91, pp. 1-21.

Frischknecht, R. ym., 1996. *Ökoinventar für Energiesysteme,* Zurich: ETH Zurich.

Goedkoop, M. H. R. H. M. S. A. S. v. Z., 2009. *ReCiPe 2008. Report I: Characterisation,* s.l.: Ministry of Housing, Spatial Planning and Environment (VROM).

GreenDelta, 2016a. *openLCA 1.5. Basic modelling.,* Berlin, Germany: GreenDelta.

GreenDelta, 2016b. *ELCD 3.2 in openLCA,* Berlin: GreenDelta.

Homa, J. & Hoffman, E., 2014. *Life Cycle Analysis of Leading Coagulants: Executive Summary,* s.l.: INCOPA.

Igos, E. et al., 2014. Life Cycle Assesment of water treatment: what is the contribution of infrastructure and operation at unit process level?. *Journal of Cleaner Production,* Volume 65, pp. 424-431.

Igos, E. et al., 2013. Cost-performance indicator for comparative environmental assessment of water treatment plants. *Science of the Total Environment,* Volume 443, pp. 367-374.

IPCC, 2007. *Climate change 2007: Synthesis Report. Contribution of Working Groups I,II,and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change,* Geneva: IPCC.

ISO, 2006a. *14040 International Standard. Environmental Management-Life Cycle Assessement-Principles and Framework.,* Geneva, Switzerland: International Organisation for Standardization.

ISO, 2006b. *14044 International standard. Environmental Management-Life Cycle Assessment-Requirements and guidelines,* Geneva, Switzerland: International Organization for Standardization.

Kros J. 2002. Evaluation of biogeochemical models at local and regional scale. PhD thesis. Wageningen University,Wageningen, The Netherlands.

Meier, M., 1997. *Eco-Efficiency Evaluation of Waste Gas Purification Systems in the Chemical Industry,* Zurich: Swiss federal institute of technology Zurich.

Mohapatra, P. et al., 2002. Improving eco-efficiency of Amsterdam water supply: A LCA approach. *Journal of Water Supply: Research and Technology—AQUA,* 51(4), pp. 217-227.

OpenLCA Nexus, 2017a. *OpenLCA Nexus. Updated 16.11.2017. Visited 10.12.2017.*
Available at: https://nexus.openlca.org/database/ELCD

OpenLCA Nexus, 2017b. *OpenLCA Nexus. Updated 16.11.2017. Visited 10.12.2017*
Available at: https://nexus.openlca.org/database/bioenergiedat

Raluy, R. G., Serra, L. & Uche, J., 2005a. Life Cycle Assessment of Water Production Technologies. Part 1: Life Cycle Assessment of Different Commercial Desalination Technologies (MSF, MED, RO). *Int J LCA,* 10(4), pp. 285-293.

Raluy, R. G., Serra, L., Uche, J. & Valero, A., 2005b. Life Cycle Assessment of Water Production Tecnologies. Part 2: Reverse Osmosis Desalination versus the Ebro River Water Transfer. *Int J LCA,* 10(5), pp. 346-354.

Ribera, G. et al., 2014. Life cycle and human health risk assessments as tools for decision making in the design and implementation of nanofiltration in drinking water treatment plants. *Science of the Total Environment,* Volume 466, pp. 377-386.

Sala, S., Pant, R. & Hauschild, M. &. P. D., 2012. Research Needs and Chaalllenges from Science to Decision Suppport. Lesson Learnt from the Development of the International Reference Life Cycle Data System (ILCD) Recommendations for Life Cycle Impact Assessment. *Sustainability,* Osa/vuosikerta 4, pp. 1412-1425.

WMO, 2002. *Scientific Assessment of Ozone Depletion: Global Ozone Research and Monitoring Project,* s.l.: World Meteorological Organization.

van Zelm, R., Huijbregts, Mark A.J., van Jaarsveld, Hans A., Jan Reinds, G., Struijs, J. & van de Meent, Dik. 2007. Time horizon dependent characterization factors for acidification in life-cycle assessment based on forest plant species occurrence in Europe. Environmental Science & Technology 41, 922-927.

Van Jaarsveld, JA. 1995. Modelling the long-term atmospheric behaviour of pollutants on various spatial scales.
PhD thesis. University of Utrecht, Utrecht, The Netherlands.

Vince, F., Aoustin, E., Bréant, P. & Marechal, F., 2008. LCA tool for the environmental evaluation of potable water production. *Desalination,* Volume 220, pp. 37-56.

8 Miscellaneous Sources

Poutanen, H. 2017a. HSY. Personal communication. E-mail received 10.3.2017 and 28.4.2017.

Poutanen, H. 2017b. HSY. Personal communication. E-mail received 4.4.2017.

Hesampour, M. and Kettunen, V. 2017. Kemira. Personal communication.

Rannali, M. 2017. Nordkalk. Personal communication. 25.4.2017.

Pöyry. 2016. Ympäristölupahakemus. Tytyrin kalkkitehdas, Lohja. Nordkalk Oy AB.

Ylisuutari. S. 2017. Yara. Personal communication. E-mail received 22.9.2017.

Kettunen, T. 2017. HSY. Personal communication. E-mail received 4.5.2017.

9 List of Appendices

1 Appendices

Appendix I. The minimum microbiological drinking water quality standards of European Union (EC, 1998).

Microbiological parameters

Parameter	Parametric value (number/100 ml)
Escherichia coli (E. coli)	0
Enterococci	0

Appendix II. The minimum chemical drinking water quality standards of European Union (EC, 1998).

Chemical parameters

Parameter	Parametric value	Unit	Notes
Acrylamide	0,10	μg/l	Note 1
Antimony	5,0	μg/l	
Arsenic	10	μg/l	
Benzene	1,0	μg/l	
Benzo(a)pyrene	0,010	μg/l	
Boron	1,0	mg/l	
Bromate	10	μg/l	Note 2
Cadmium	5,0	μg/l	
Chromium	50	μg/l	
Copper	2,0	mg/l	Note 3
Cyanide	50	μg/l	
1,2-dichloroethane	3,0	μg/l	
Epichlorohydrin	0,10	μg/l	Note 1
Fluoride	1,5	mg/l	
Lead	10	μg/l	Notes 3 and 4
Mercury	1,0	μg/l	
Nickel	20	μg/l	Note 3
Nitrate	50	mg/l	Note 5
Nitrite	0,50	mg/l	Note 5
Pesticides	0,10	μg/l	Notes 6 and 7
Pesticides — Total	0,50	μg/l	Notes 6 and 8
Polycyclic aromatic hydrocarbons	0,10	μg/l	Sum of concentrations of specified compounds; Note 9
Selenium	10	μg/l	
Tetrachloroethene and Trichloroethene	10	μg/l	Sum of concentrations of specified parameters
Trihalomethanes — Total	100	μg/l	Sum of concentrations of specified compounds; Note 10
Vinyl chloride	0,50	μg/l	Note 1

Note 1: The parametric value refers to the residual monomer concentration in the water as calculated according to specifications of the maximum release from the corresponding polymer in contact with the water.

Appendix III. Inventory data of chemicals.

Resource	***Amount***	***Unit***	***More information***
Ferric sulfate:			
Ferric sulfate	4.00893E-05	t/m3	
Sulphuric acid	1.42317E-06	t/m3	
Drinking water	3.08688E-06	m3/m3	
Natural gas	0.000286639	m3/m3	
Electricity	0.001254795	MJ/m3	
Trasportation by truck	0.000274451	tkm/m3	
Transportation by ship	0.060534863	tkm/m3	
Transportation	0.000391984	tkm/m3	Articulated lorry transport, capacity 27 t
Ammonia water:			
Ammonia water	5.93579E-07	t/m3	25 %
Nitrogen	confidential		
Energy	confidential		
Natural gas	confidential		
Transportation	8.90368E-06	tkm/m3	Transportation, capacity 27 t
Sodium hypochlorite:			
Sodium hypochlorite	4.13409E-06	t/m3	10 %
Salt	confidential	t/m3	
Energy	confidential	MJ/m3	
Deionised water	confidential	m3/m3	
Natural gas	confidential	m3/m3	
Furnace oil (extra light)	confidential	t/m3	
Electricity UCPTE	confidential	MJ/m3	
Transportation	3.81255E-05	tkm/m3	Transportation, capacity 27 t
Limewater production:			
Burnt lime	7.15263E-06	t/m3	
Limestone	1.2766E-05	t/m3	
Transportation by ship	1.0677E-06	tkm/m3	Container ship, 27500 t
Trasportation by truck	4.34989E-05	tkm/m3	Articulated lorry, 27 t
Coal	2.94599E-06	t/m3	
Heavy fuel oil	1.964E-08	t/m3	
Electricity mix	0.012019914	MJ/m3	

Appendix IV. Inventory data of other raw material

Resource	***Amount***	***Unit***	***More information***
Limestone for sand filtration:			
Limestone	2.83329E-05	t/m3	
Transportation	0.00018259	tkm/m3	Articulated lorry transport, 27 t truck capacity
GAC (production, regeneration, disposal):			
GAC	1.94E-09	t/m3	
Hard coal	4.83E-09	t/m3	
Transportation	1.60E-06	tkm/m3	
Electricity	2.60E-07	MJ/m3	
Hydrogen chloride gas	3.11E-11	t/m3	
Natural gas	2.03E-05	m3/m3	
Deionised water	7.71E-09	t/m3	
Process steam from light fuel oil	5.63E-11	t/m3	
Disposed GAC	1.34E-09	t/m3	
CO2 production:			
CO2	5.88836E-06	t/m3	
Transportation	1.28808E-05	tkm/m3	Lorry transport, 16 t
Oxygen for production of ozone:			
Oxygen	6.17E-06	t/m3	
Transportation	6.74392E-05	tkm/m3	Lorry transport, 16 t

Appendix V. Inventory data of infrastructure.

Infrastructure	
Resource	***Amount (t/m3)***
Pre-cast concrete	4.05E-05
Steel rebar	1.11E-06
Tile	9.48E-07
Light weight concrete block	8.88E-07
Glass wool	7.83E-07
Gravel	8.25E-07
Stainless steel	7.85E-08
Steel hot-dip galvanised coil	4.61E-08
Porcelain	1.54E-07
Sand	4.13E-06
Glass	1.14E-09
Aluminium	1.15E-08
Mercury	7.23E-14
Copper wire	1.93E-11
Carbon	8.08E-10
Iron	2.5E-08
Silicon	5.49E-10
PE-HD	1.69E-10
PP fibre	3.68E-11
Copper sheet	3.83E-10
Zinc	7.28E-11
Tin	1.76E-11

Manganese	6.4E-12
Magnesium	1.28E-12
Phosphorus	8.53E-13
Sulfur	4.27E-13

Appendix VI. Inventory data of transportation of infrastructure.

Transportation of infrastructure		
Resource	***Amount*** (t/m3)	***More information***
Pre-cast concrete	0.000915	Articulated lorry transportation 27 t
Tile	2.14E-05	Articulated lorry transportation 27 t
Glass wool	1.77E-05	Articulated lorry transportation 27 t
Light weight concrete block	2.01E-05	Articulated lorry transportation 27 t
Steel rebar transport from Lithuania:		
truck	2.21E-05	Articulated lorry transportation 27 t
ship	3.5E-09	Container ship transportation 27 500 t

Appendix VII. Infrastructure of water treatment process.

Chemical precipitation, flocculation and settling				
	V [m3]	ρ [kg/m3]	m [t]	m [t]/m3
Concrete	15556	2400	37335	2.3678E-05
Steel rebar	163	7850	1276	8.0908E-07
Tile	301	1450	436	2.767E-07
Mineral wool (soft insulation)	1106	525	581	3.6837E-07
Polystyrene (stiff insulation)	78	24	2	1.1817E-09
Light gravel	2753	290	798	5.064E-07
Stainless steel (Flocculators)	0.3	7850	2	1.2684E-09

FeSO chemical storage				
	V [m3]	ρ [kg/m3]	m [t]	m [t]/m3
Concrete	89	2400	213	1.35E-07
Steel rebar	0	7850	3	2.0909E-09
Tile	42	1450	61	3.8623E-08
Mineral wool (soft insulation)	52	525	27	1.718E-08
Polystyrene (stiff insulation)	14	24	0.3	2.1309E-10
Light gravel	29	290	8	5.2968E-09
Acid-resisting steel (tanks)	1	7850	5	3.4007E-09

Sand filtration				
	V [m3]	ρ [kg/m3]	m [t]	m [t]/m3
Concrete	4413	2400	10591	6.717E-06
Steel rebar	43	7850	339	2.1514E-07
Sand	3387	1922	6510	4.1284E-06
Tile	254	1450	368	2.334E-07
Mineral wool (soft insulation)	496	525	260	1.6519E-07
Polystyrene (stiff insulation)	65	24	2	9.8727E-10

Light gravel	1011	290	293	1.8599E-07
Gravel	1016	1280	1301	8.2481E-07
Porcelain (filtration module element)	101	2400	243	1.543E-07
Contact basin (under sand filtration)				
Concrete	2388	2400	5732	3.635E-06
Steel rebar	96	7850	229	1.454E-07

Ozonation				
	V [m3]	ρ [kg/m3]	m [t]	m [t]/m3
Concrete	276	2400	662	4.2E-07
Steel rebar	4	7850	34	2.1815E-08
Tile	89	1450	129	8.1864E-08
Mineral wool (soft insulation)	136	525	71	4.5211E-08
Polystyrene (stiff insulation)	28	24	1	4.2155E-10
Light gravel	158	290	46	2.9077E-08
Stainless steel (ozonator)	1	7850	9	5.5175E-09
Glass (ozonator)			0.3	1.9026E-10

GAC filtration				
	V [m3]	ρ [kg/m3]	m [t]	m [t]/m3
Concrete	2610	2400	6263	3.9719E-06
Steel rebar	27	7850	211	1.3387E-07
Tile	159	1450	231	1.4636E-07
Mineral wool (soft insulation)	263	525	138	8.7682E-08
Polystyrene (stiff insulation)	40	24	1	6.1614E-10
Light gravel	531	290	154	9.7737E-08
GAC	2356	0.4	1	5.9772E-10
Metallic levels of working platforms:				
Aluminium (handrails)	6	2700	17	1.09E-08

Steel hot-dip galvanised coil	7	7850	56	3.56E-08

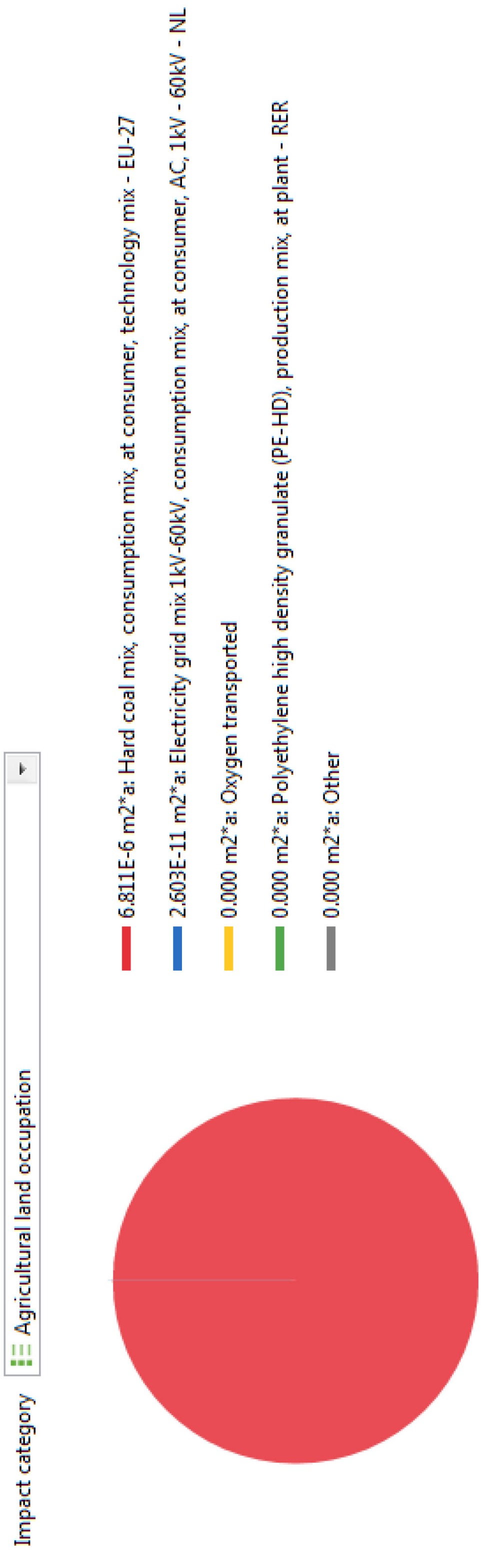
UV-disinfection	**Co-lumn1**	**Co-lumn2**	**Co-lumn3**	**Co-lumn4**	**Column5**
	V [m3]	ρ [kg/m3]	m [kg]	m [t]	
Concrete	40	2400	96000	96	6.08828E-08
Steel hot-dip galvanised coil	2.1	7850	16485	16.485	1.04547E-08
Glass			1497.2	1.4972	9.49518E-10
Stainless steel			5530.4	5.5304	3.50736E-09
Coppe			30.4	0.0304	1.92796E-11
Mercury			0.114	0.000114	7.22983E-14

Chloronation				
	V [m3]	ρ [kg/m3]	m [t]	m [t]/m3
Concrete	99	2400	237	1.5058E-07
Steel rebar	0.60	7850	5	3.0014E-09
Tile	8.38	1450	12	7.7029E-09
Mineral wool (soft insulation)	13.86	525	7	4.6148E-09
Polystyrene (stiff insulation)	2.13	24	0.05	3.2429E-11
Light gravel	27.97	290	8.11	5.1441E-09
Acid-resisting steel (tanks)	0.086	7850	0.67	4.2734E-10
Class fiber (tanks)	0.086	2600	223	1.4154E-10

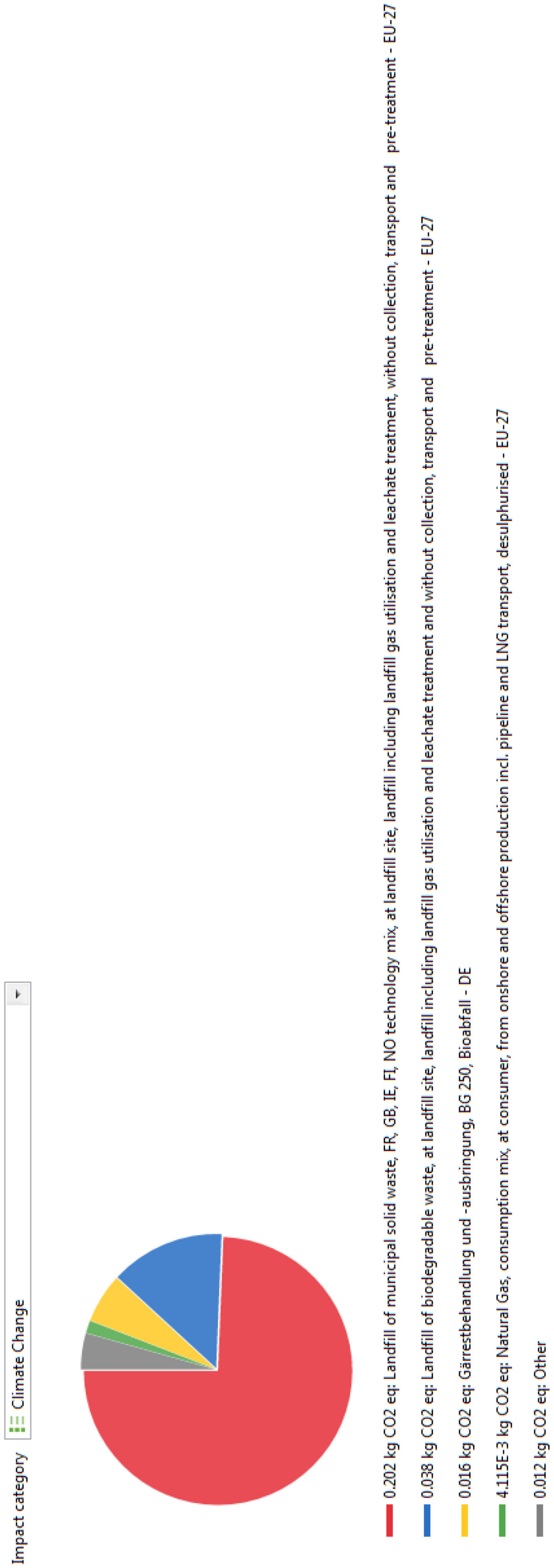
Production of limewater				
	V [m3]	ρ [kg/m3]	m [t]	m [t]/m3
Concrete	1151	2400	2764	1.7528E-06
Steel rebar	13	7850	102	6.4998E-08

Tile	178	1450	258	1.6373E-07
Mineral wool (soft insulation)	272	525	143	9.0422E-08
Polystyrene (stiff insulation)	55	24	1.3	8.4311E-10
Light gravel	316	290	92	5.8154E-08
Stainless steel (limewater equipment)	0.26	7850	2.1	1.308E-09

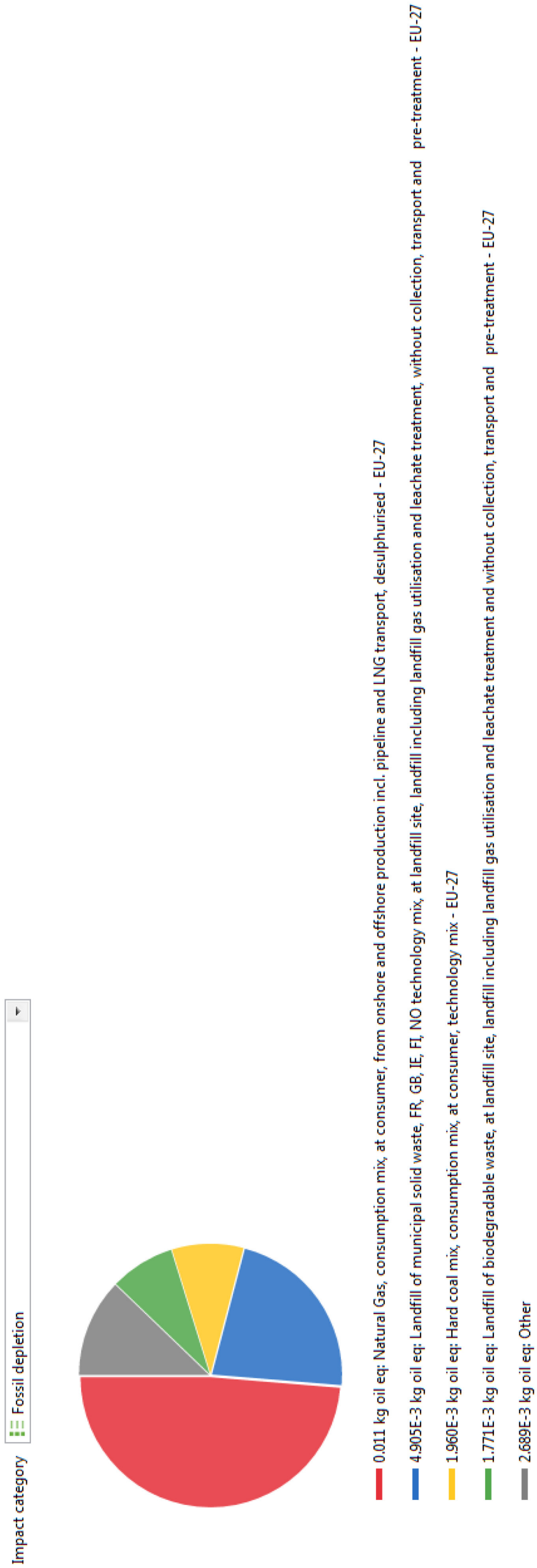
Appendix VIII. LCIA-results of agricultural land occupation with ReCiPe 2008 (H) Midpoint.



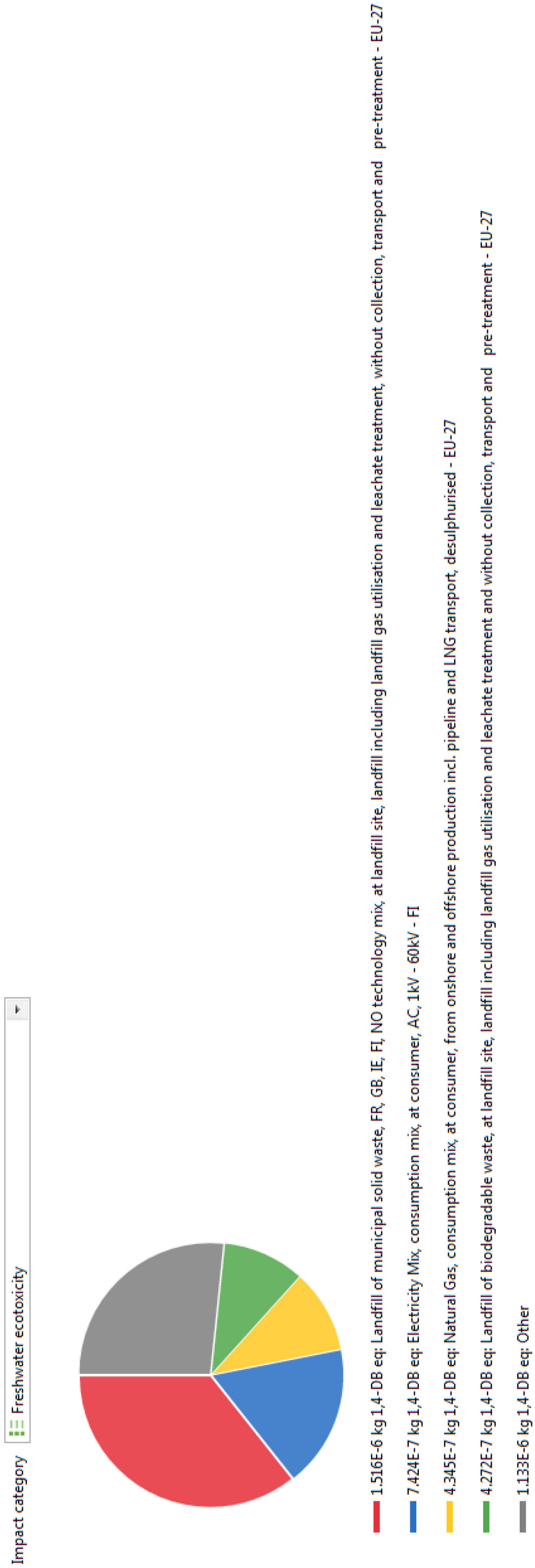
Appendix IX. LCIA-results of climate change with ReCiPe 2008 (H) Midpoint.



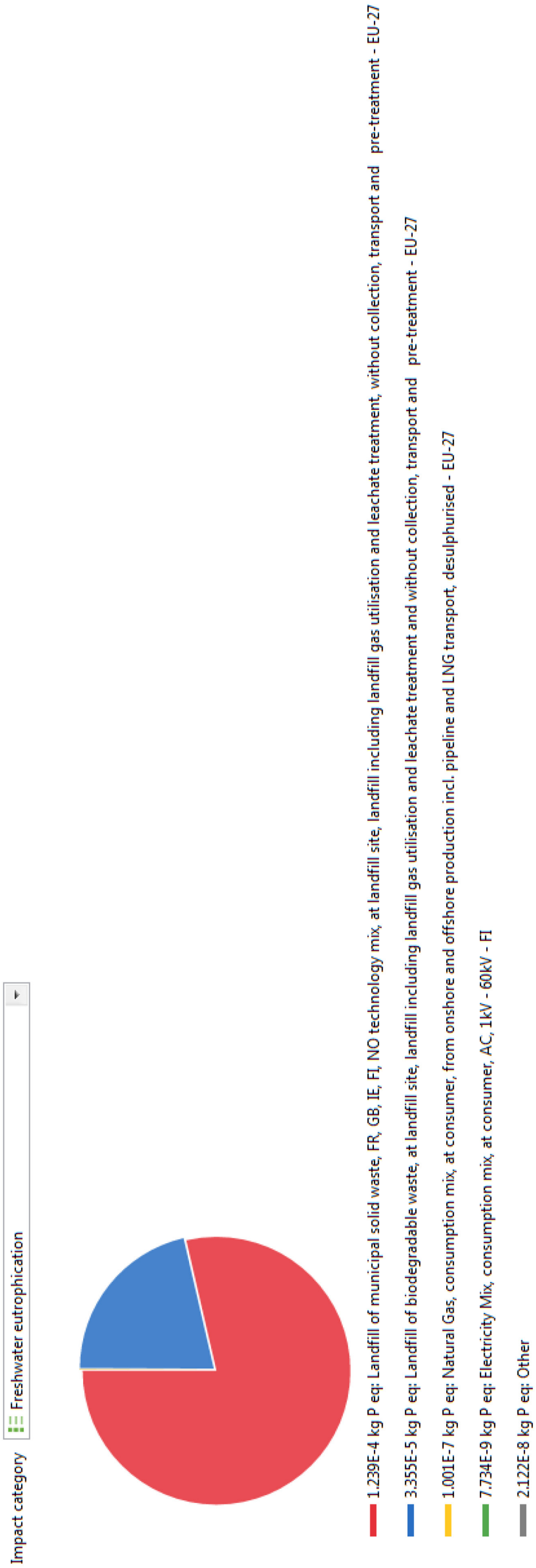
Appendix X. LCIA-results of fossil depletion with ReCiPe 2008 (H) Midpoint.



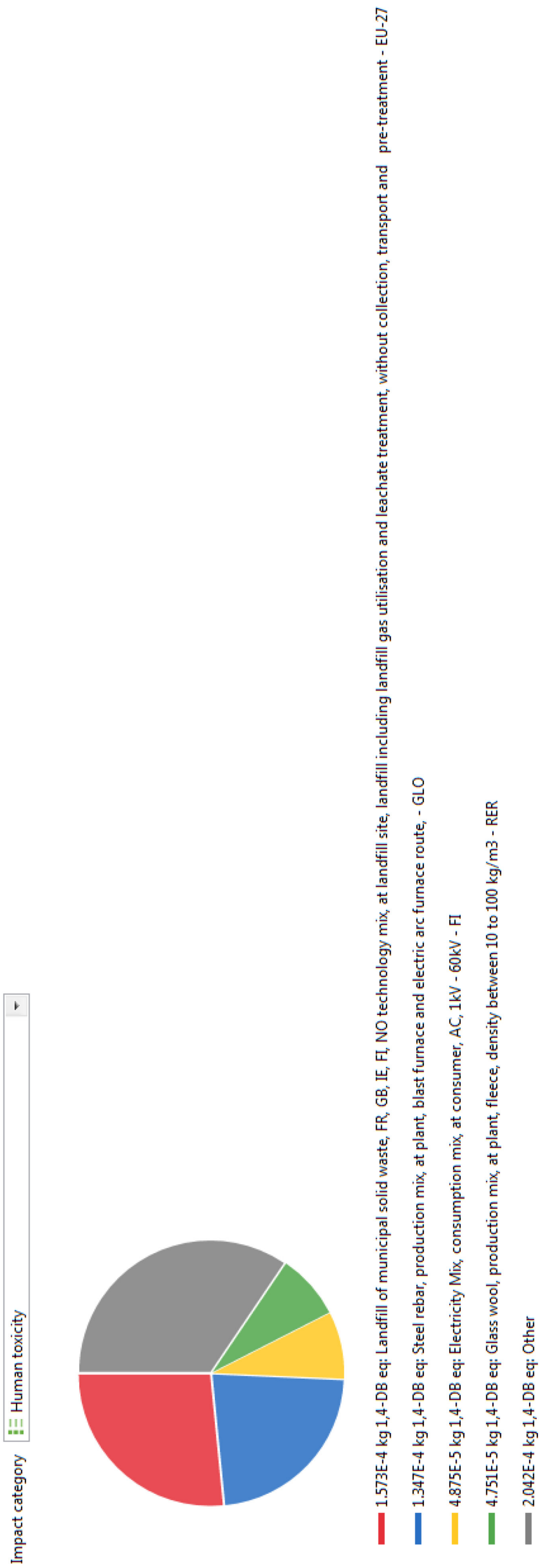
Appendix XI. LCIA-results of freshwater ecotoxicity with ReCiPe 2008 (H) Midpoint.



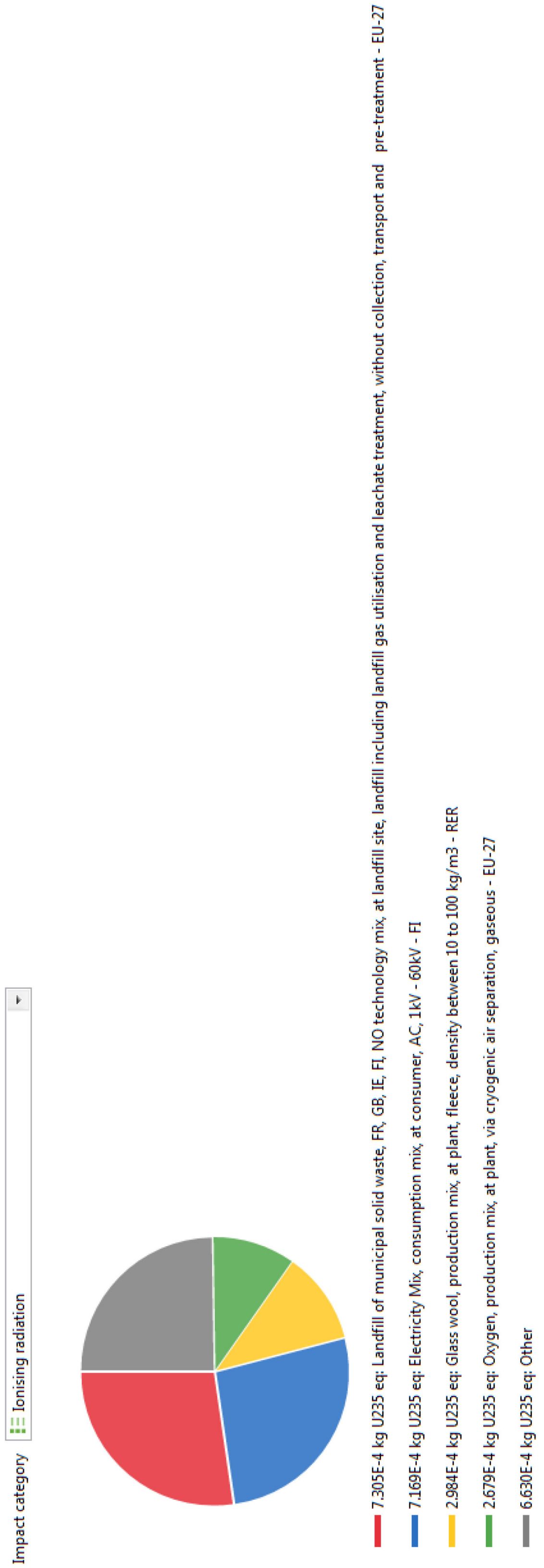
Appendix XII. LCIA-results of freshwater eutrophication with ReCiPe 2008 (H) Midpoint.



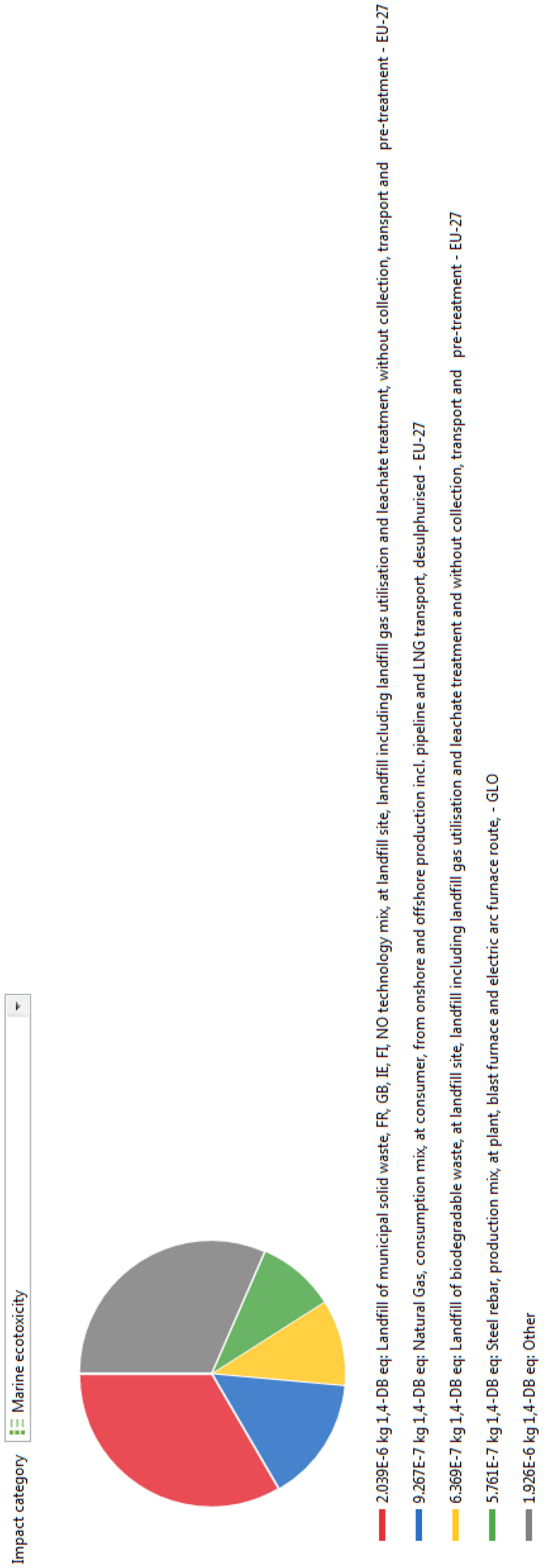
Appendix XIII. LCIA-results of human toxicity with ReCiPe 2008 (H) Midpoint.



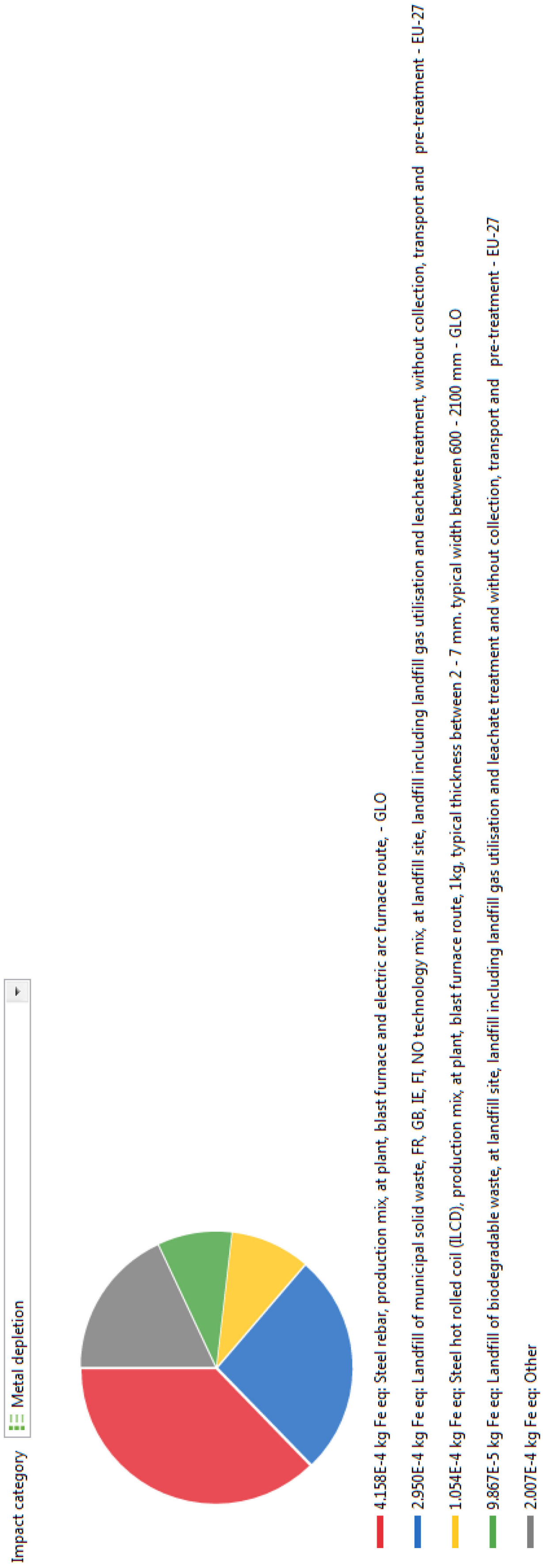
Appendix XIV. LCIA-results of ionizing radiation with ReCiPe 2008 (H) Midpoint.



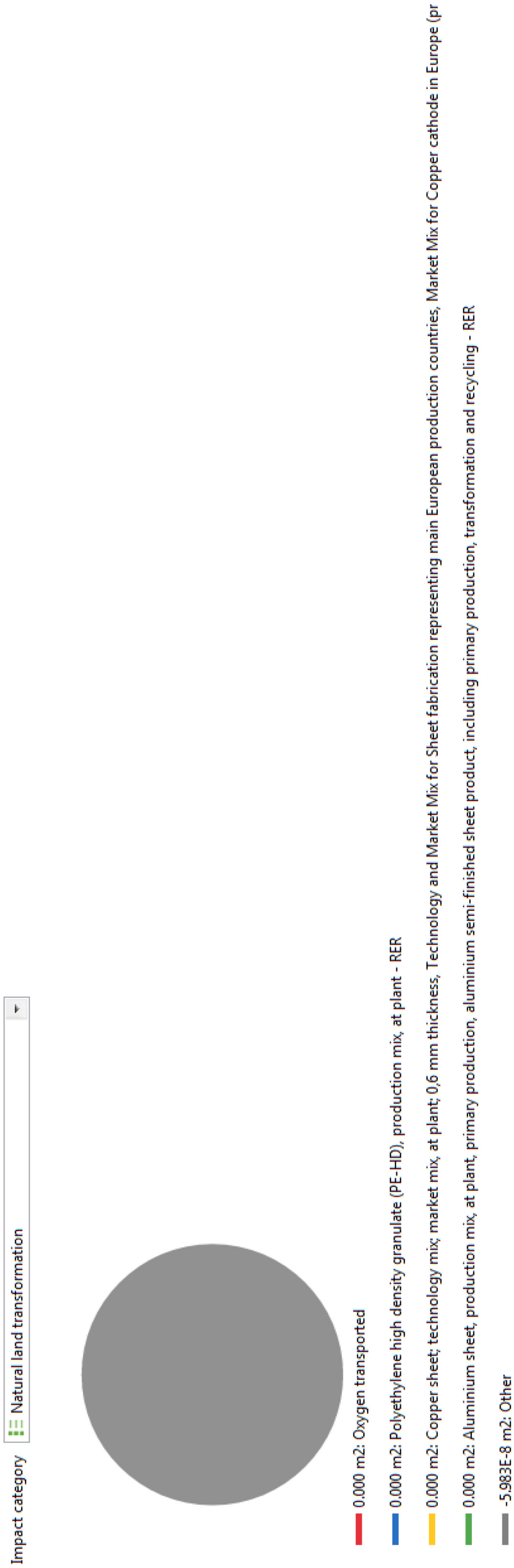
Appendix XV. LCIA-results of marine ecotoxicity with ReCiPe 2008 (H) Midpoint.



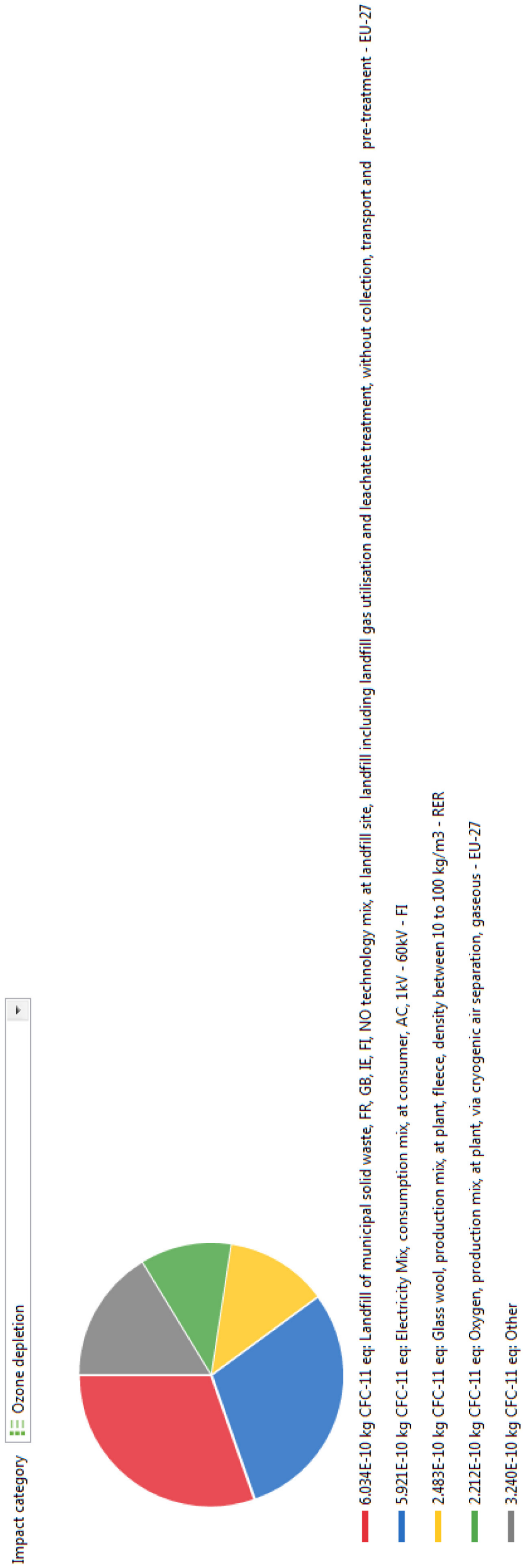
Appendix XVI. LCIA-results of metal depletion with ReCiPe 2008 (H) Midpoint.



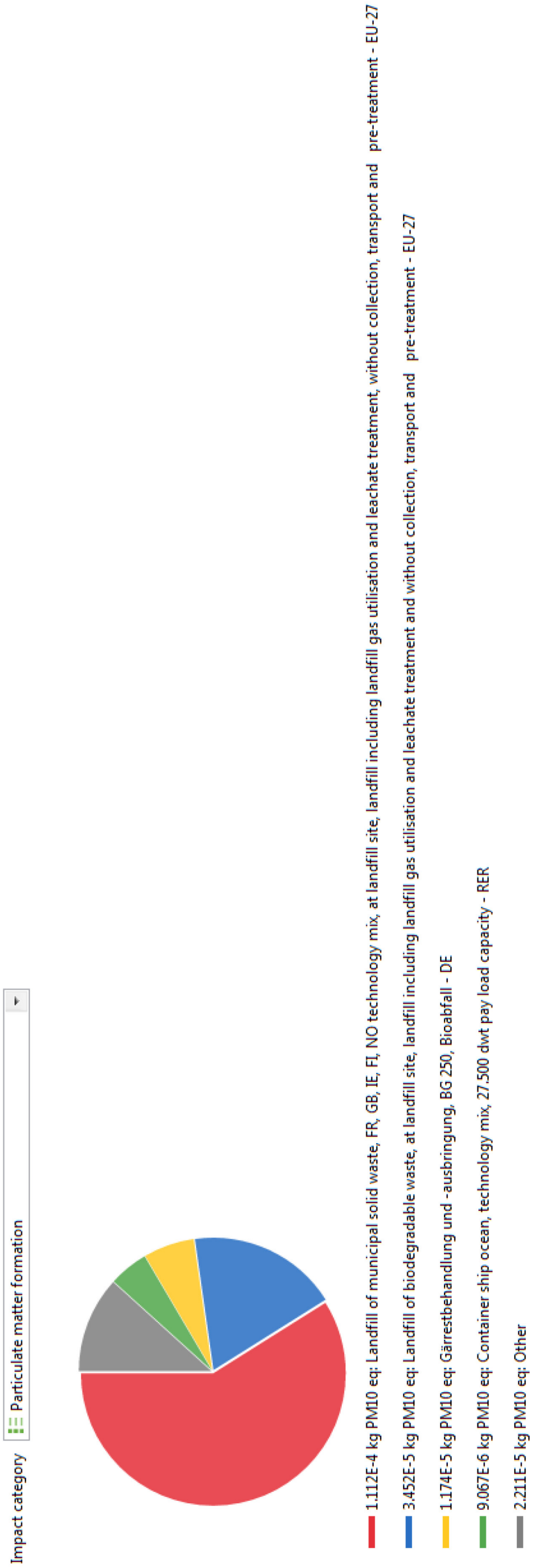
Appendix XVII. LCIA-results of natural land transformation with ReCiPe 2008 (H) Midpoint.



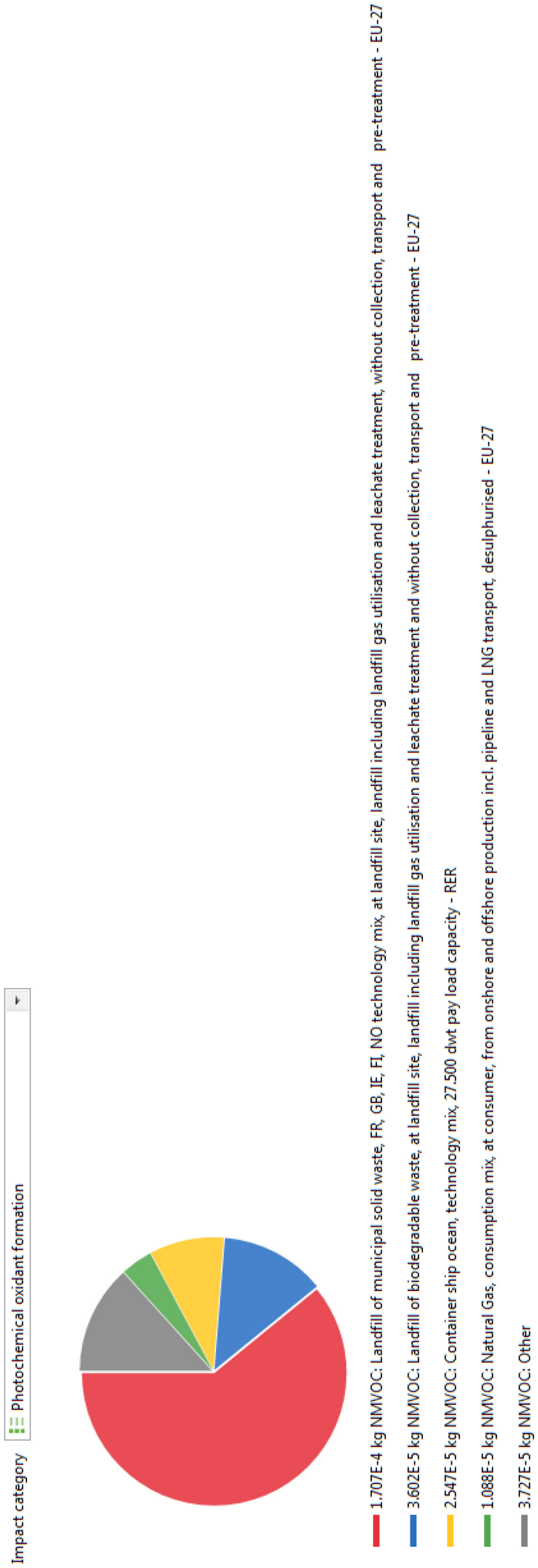
Appendix XVIII. LCIA-results of ozone depletion with ReCiPe 2008 (H) Midpoint.



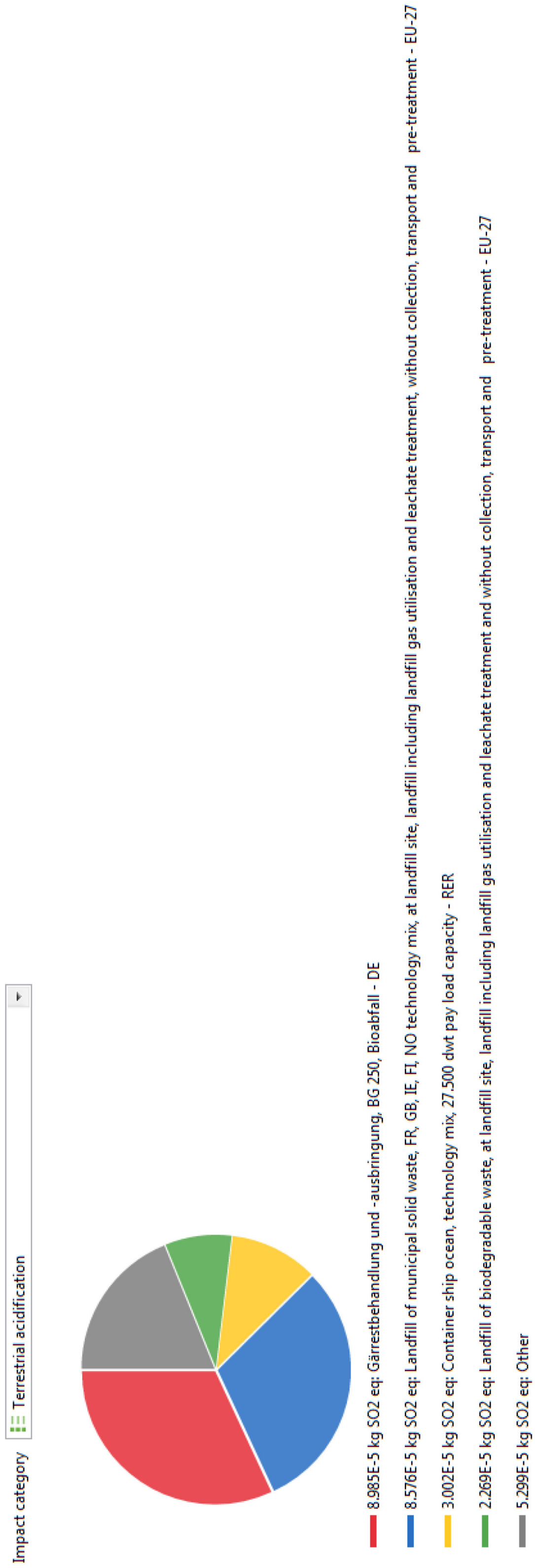
Appendix XIX. LCIA-results of particulate matter formation with ReCiPe 2008 (H) Midpoint.



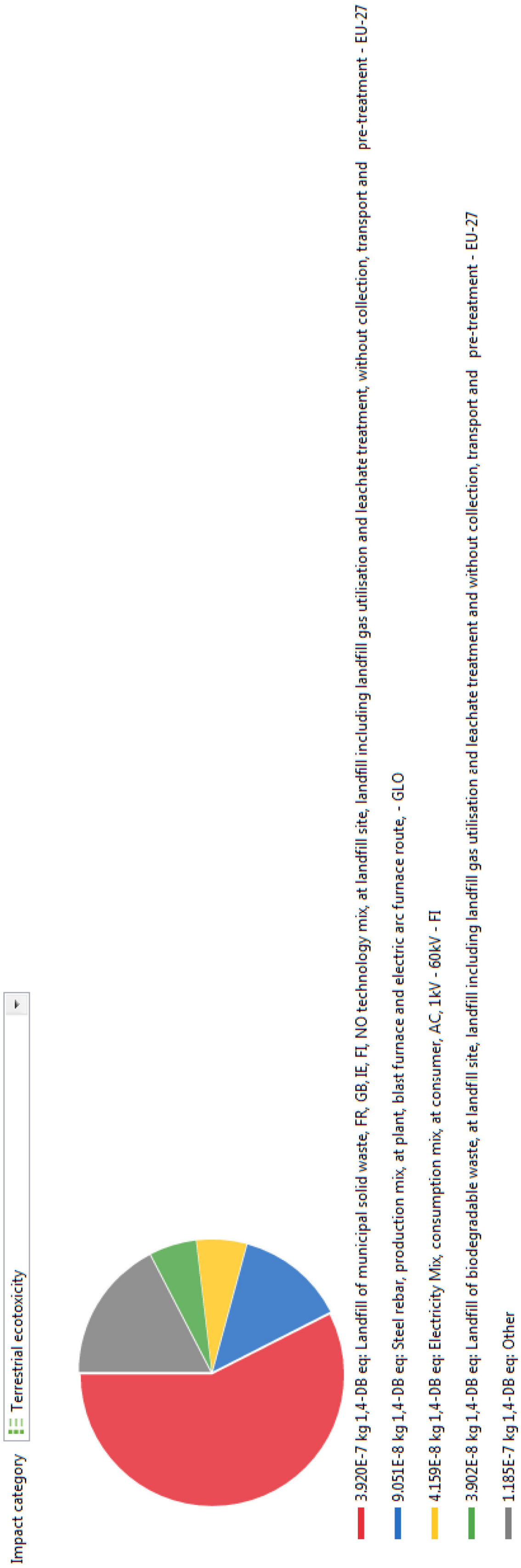
Appendix XX. LCIA-results of photochemical oxidant formation with ReCiPe 2008 (H) Midpoint.



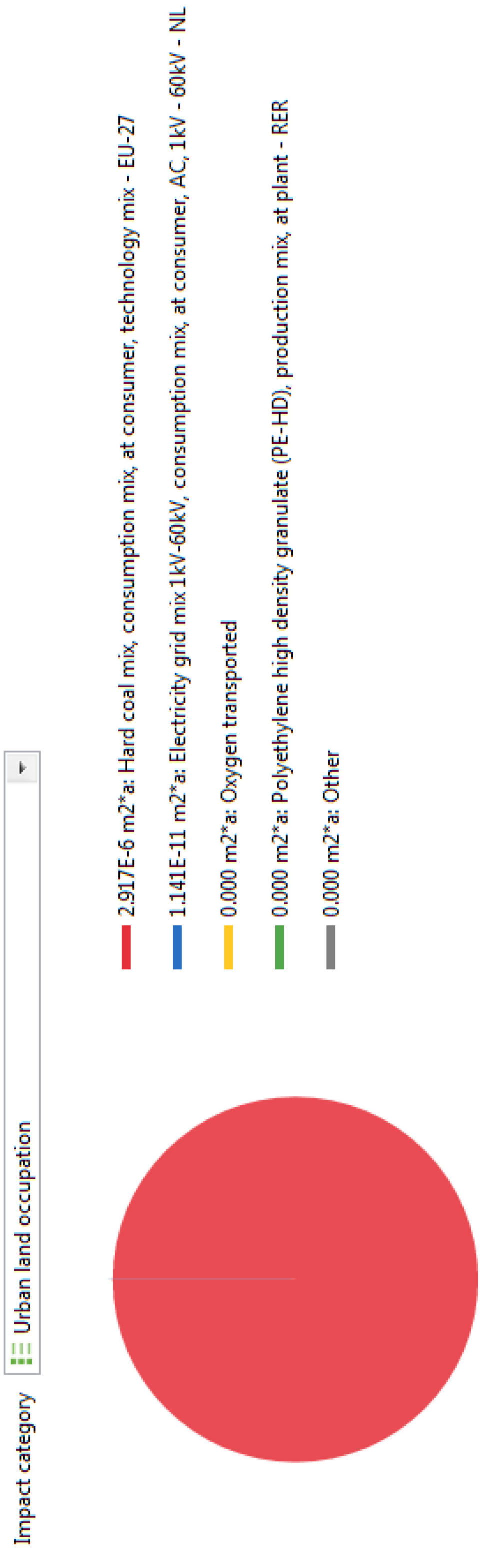
Appendix XXI. LCIA-results of terrestrial acidification with ReCiPe 2008 (H) Midpoint.



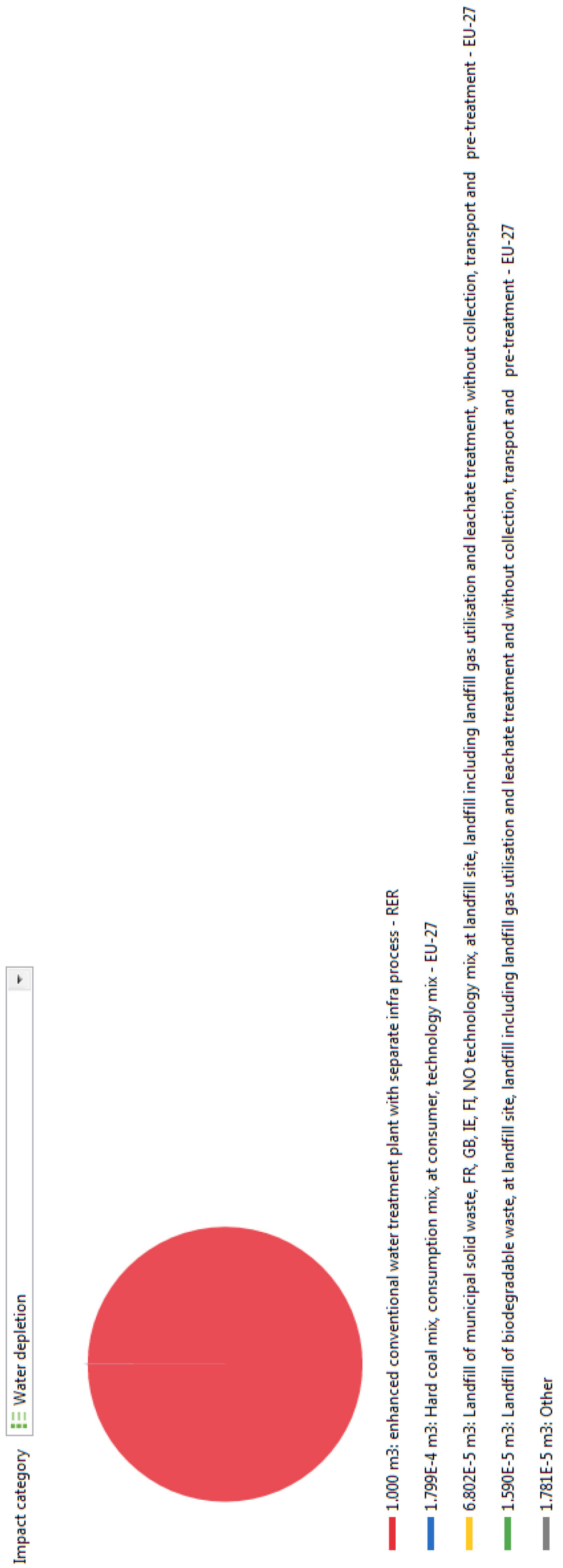
Appendix XXII. LCIA-results of terrestrial ecotoxicity with ReCiPe 2008 (H) Midpoint.



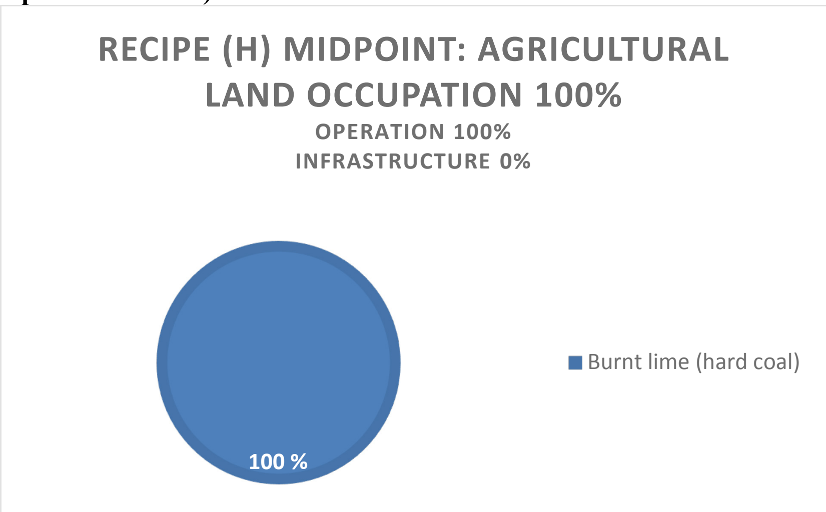
Appendix XXIII. LCIA-results of urban land occupation with ReCiPe 2008 (H) Midpoint.



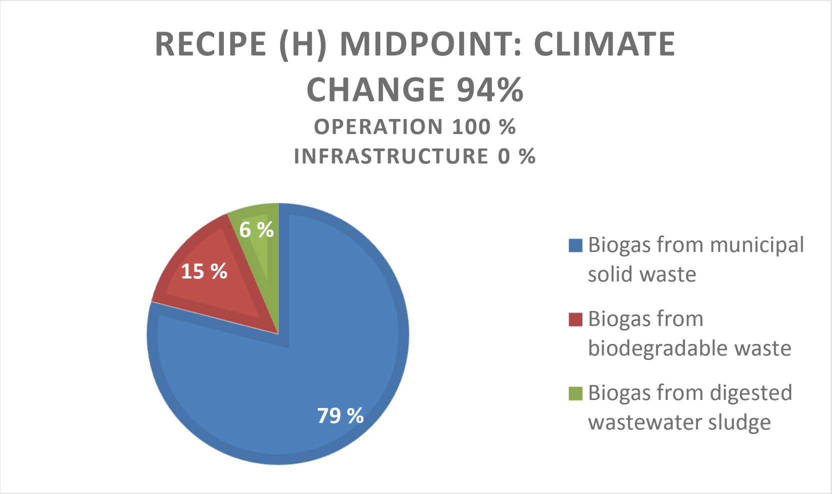
Appendix XXIV. LCIA-results of water depletion with ReCiPe 2008 (H) Midpoint.

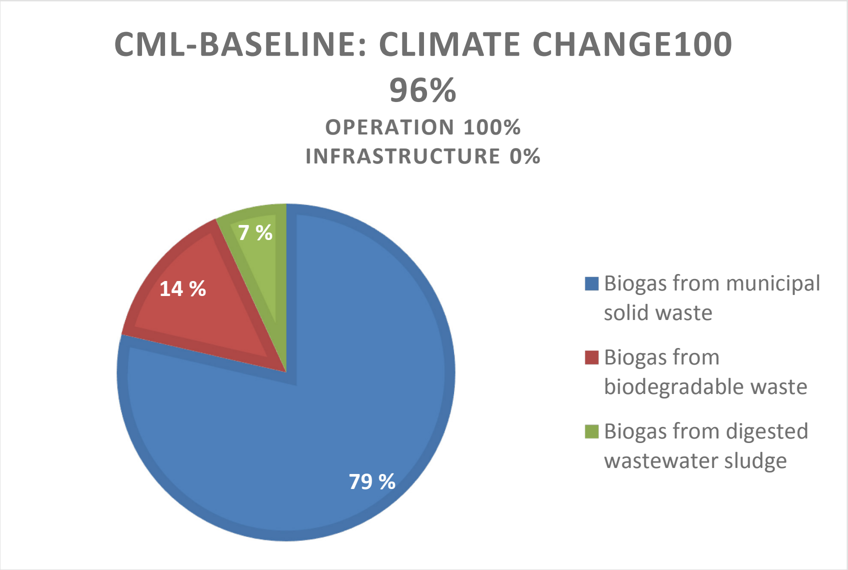


Appendix XXV. Agricultural land occupation with ReCiPe (H) Midpoint (further analyzed from OpenLCA-results).

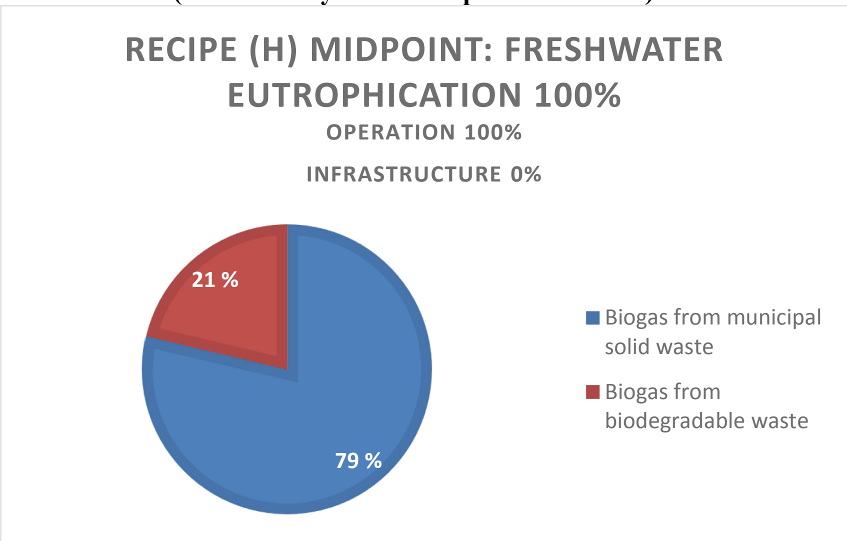


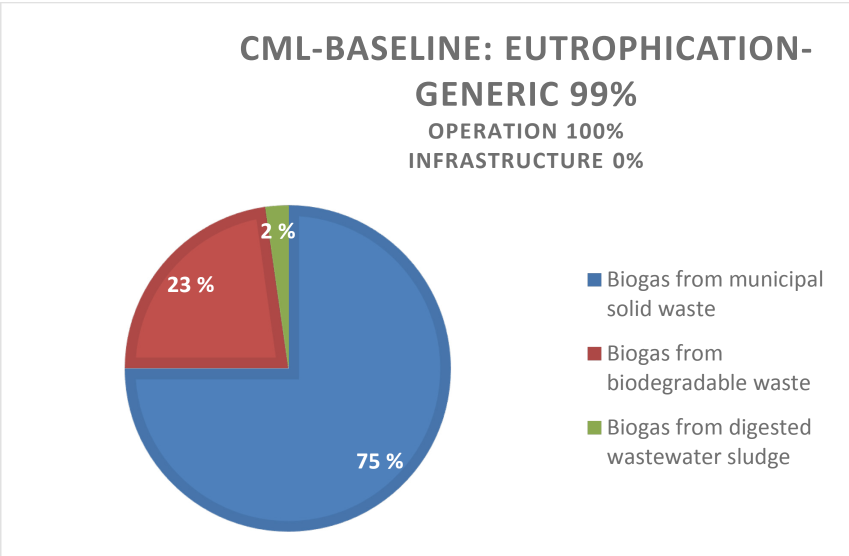
Appendix XXVI. Climate change with ReCiPe (H) midpoint and CML-Baseline (further analyzed from OpenLCA-results).



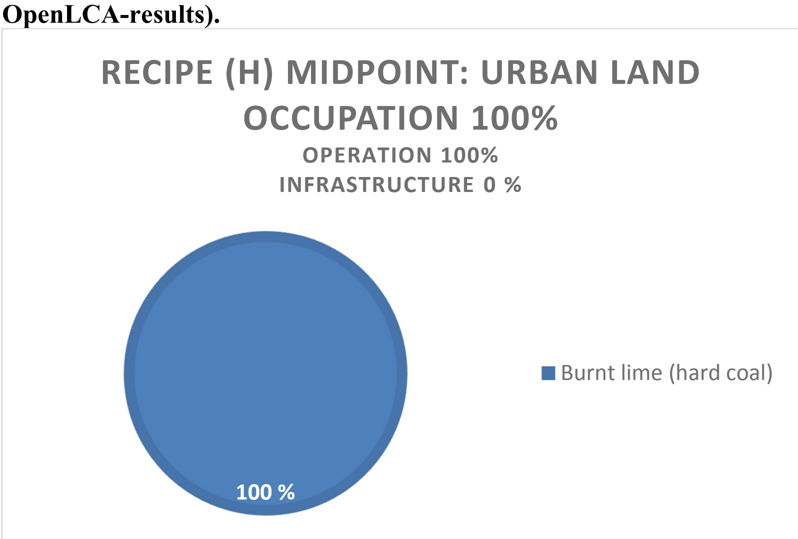


Appendix XXVII. Freshwater eutrophication with ReCiPe (H) midpoint and eutrophication with CML-Baseline (further analyzed from OpenLCA-results).

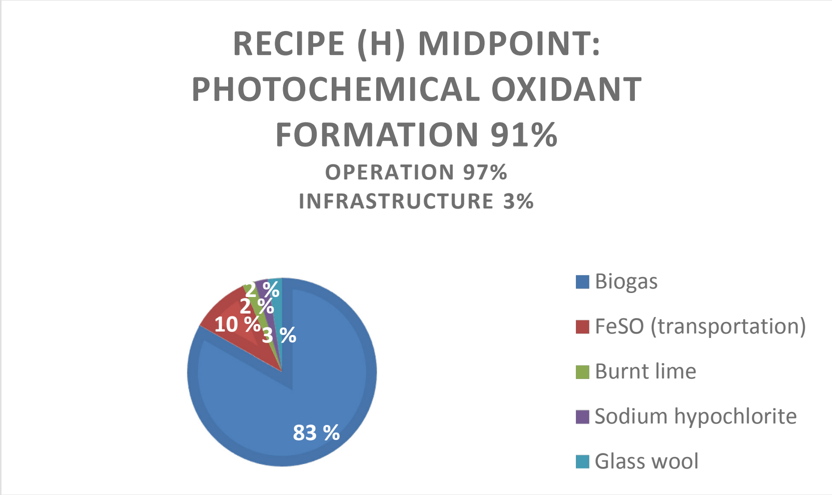


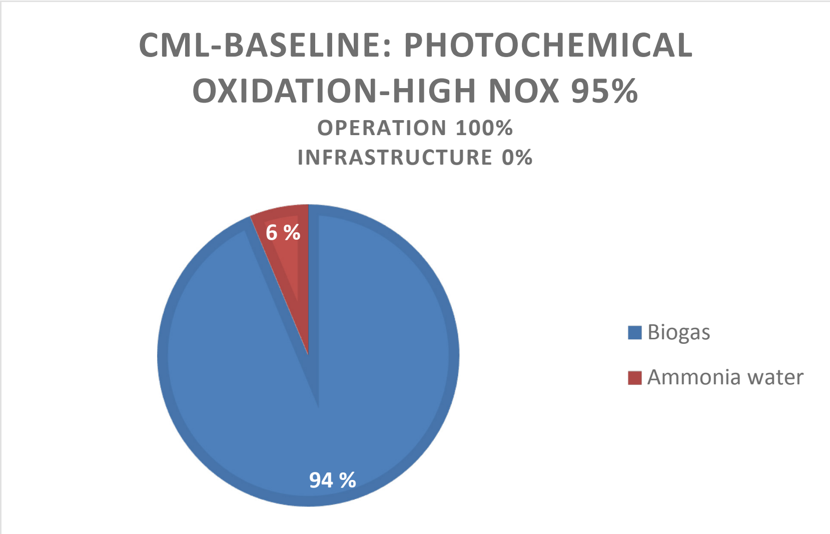


Appendix XXVIII. Urban land occupation with ReCiPe (H) Midpoint (further analyzed from OpenLCA-results).

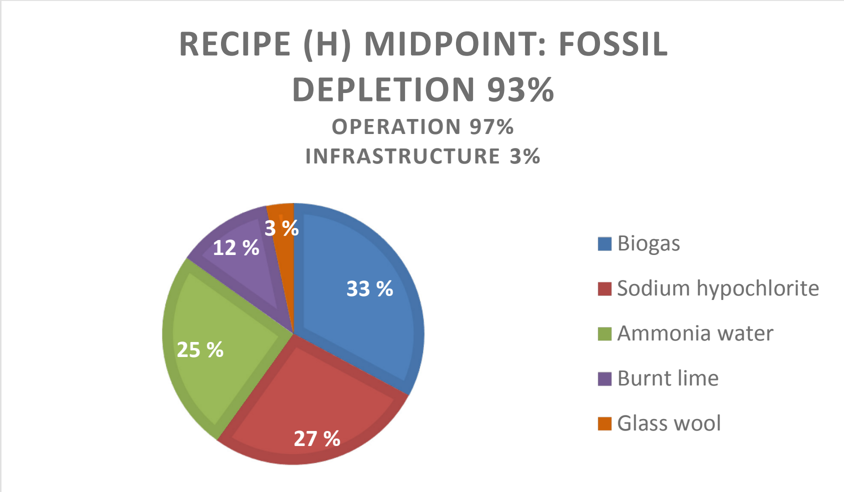


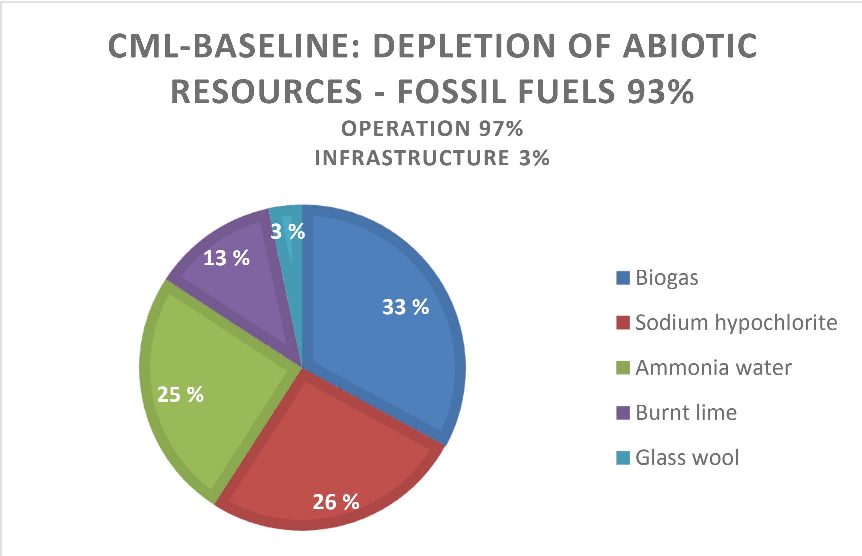
Appendix XXIX. Photochemical oxidant formation with ReCiPe (H) Midpoint and CML-Baseline (further analyzed from OpenLCA-results).



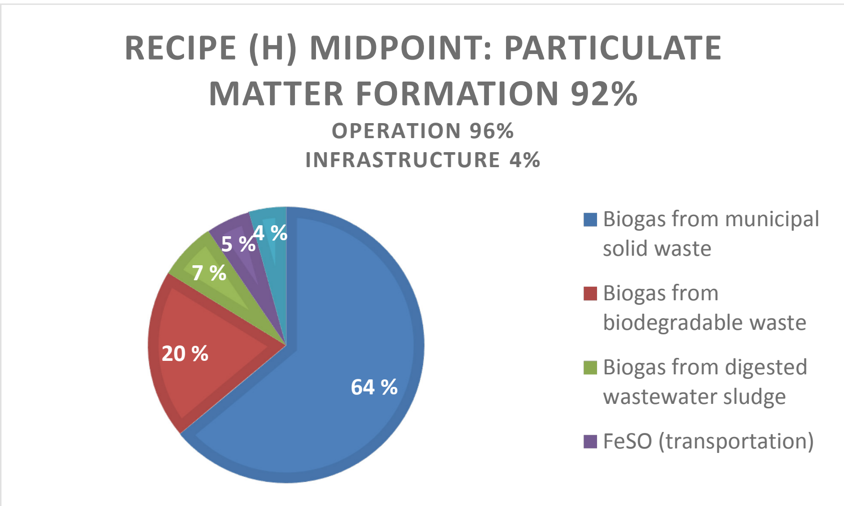


Appendix XXX. Fossil depletion with ReCiPe (H) Midpoint and CML-Baseline (further analyzed from OpenLCA-results).

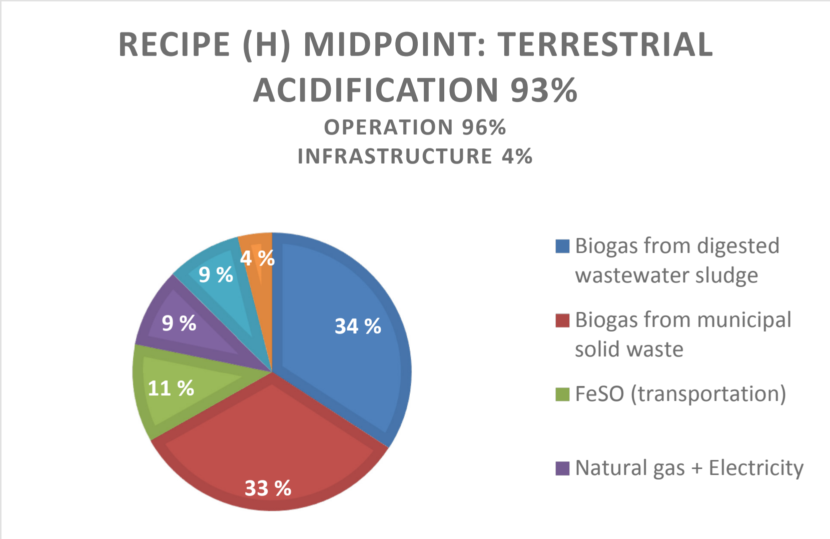


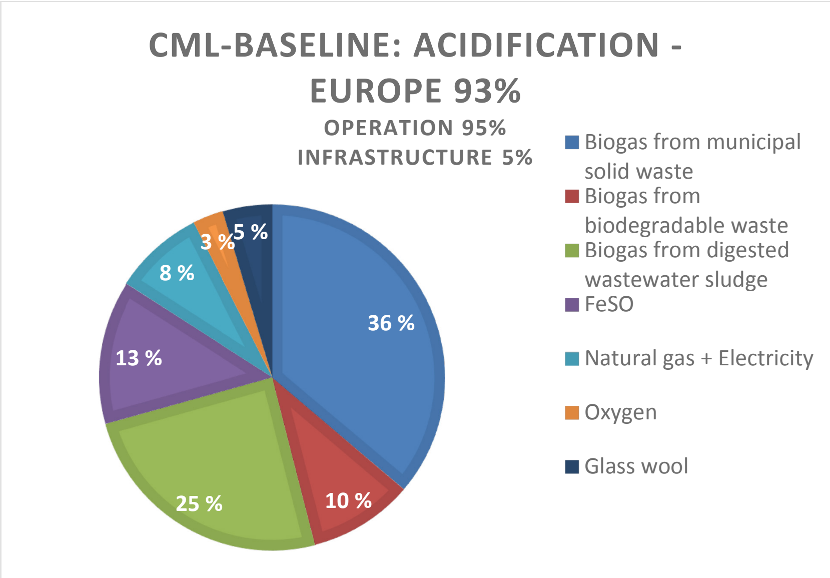


Appendix XXXI. Particulate matter formation with ReCiPe (H) Midpoint and CML-Baseline (further analyzed from OpenLCA-results).

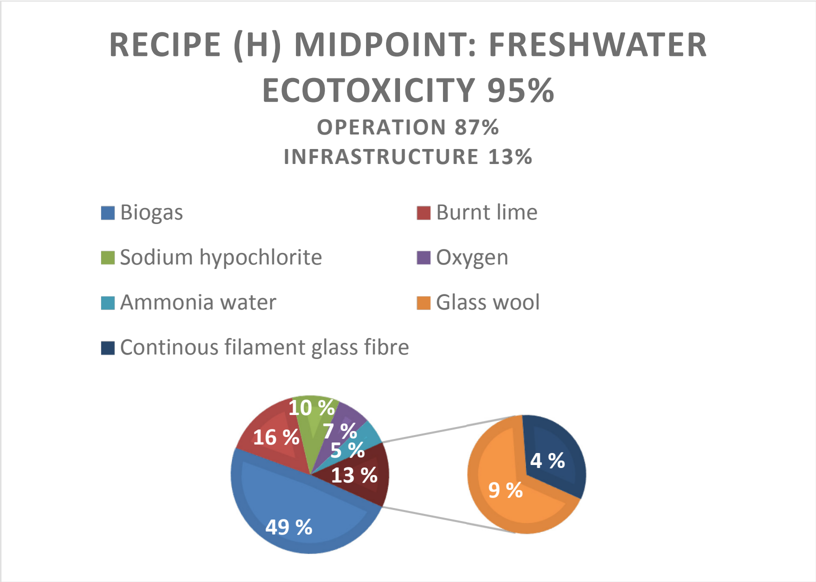


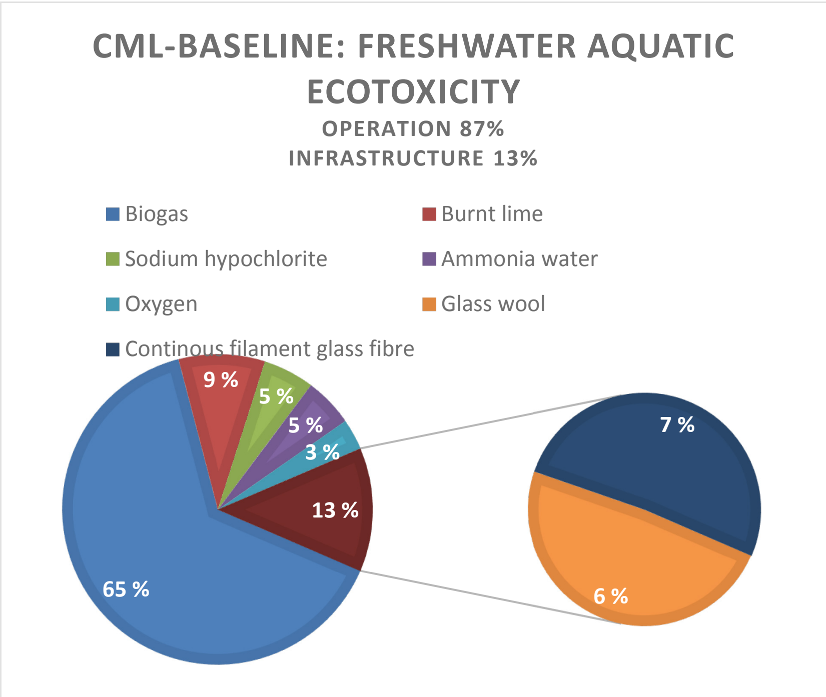
Appendix XXXII. Terrestrial acidification with ReCiPe (H) Midpoint and acidification with CML-Baseline (further analyzed from OpenLCA-results).



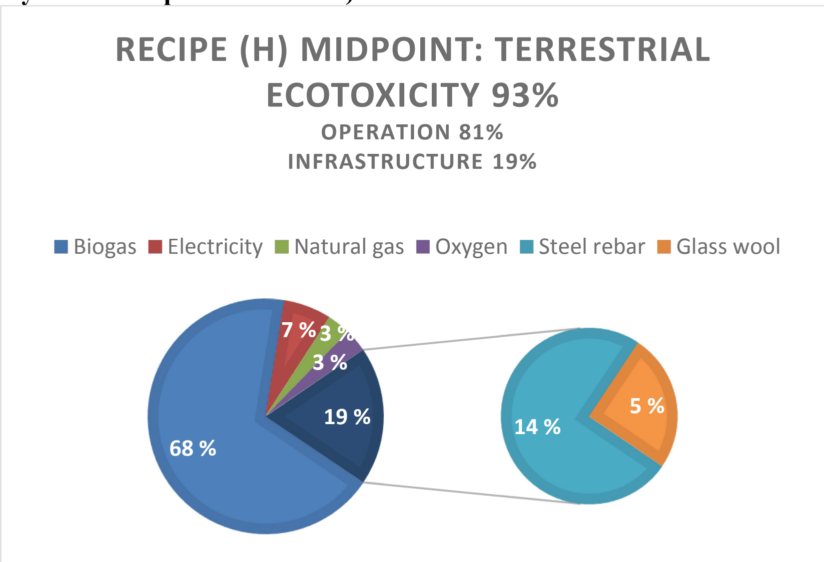


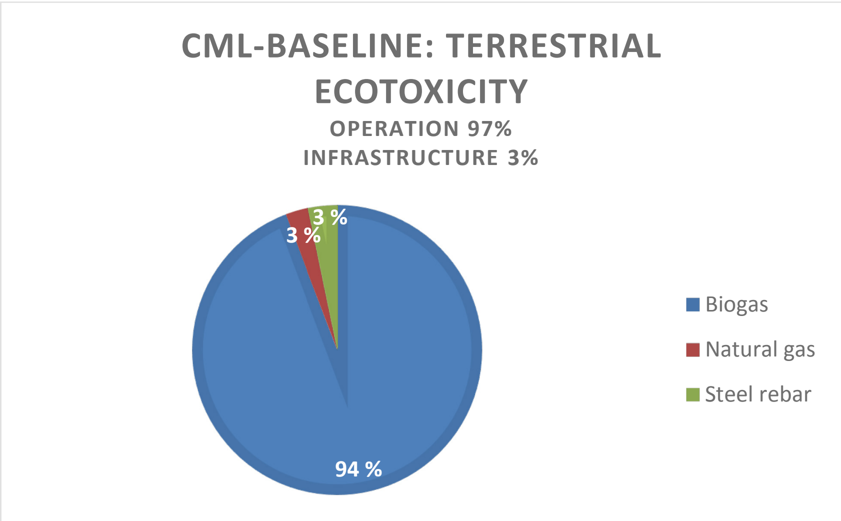
Appendix XXXIII. Freshwater ecotoxicity with ReCiPe (H) Midpoint and CML-Baseline (further analyzed from OpenLCA-results).



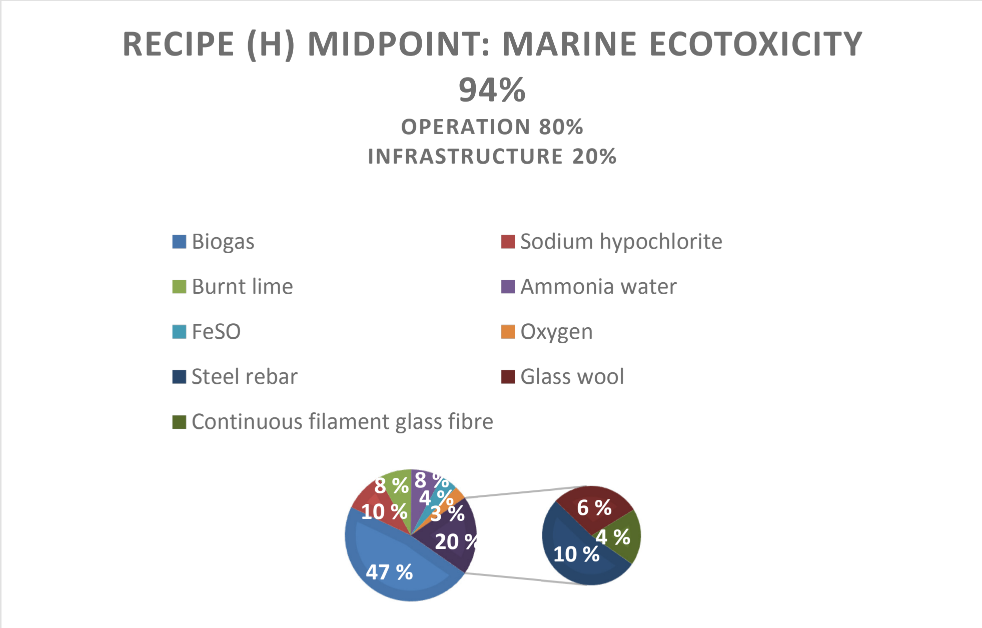


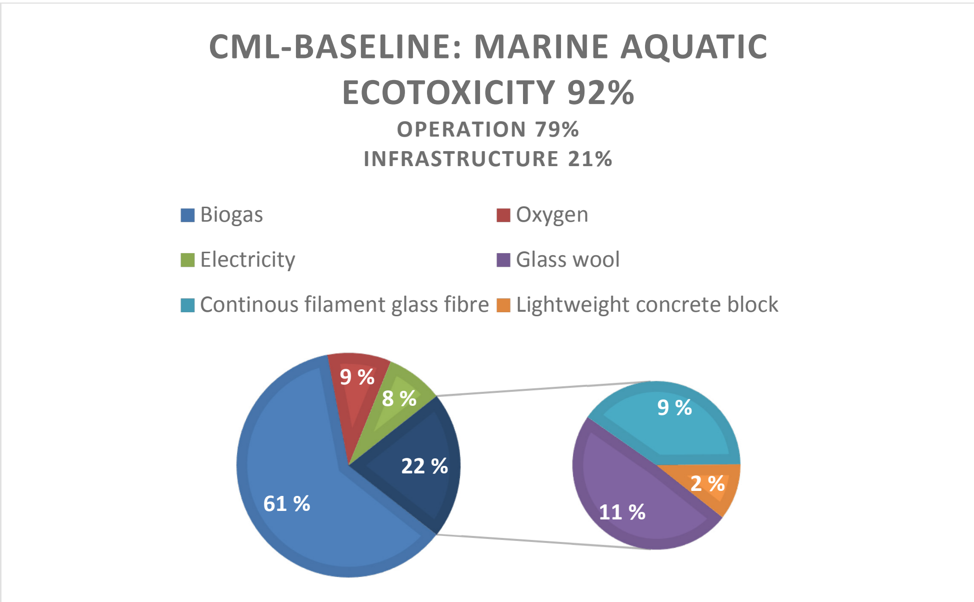
Appendix XXXIV. Terrestrial ecotoxicity with ReCiPe (H) Midpoint and CML-Baseline (further analyzed from OpenLCA-results).



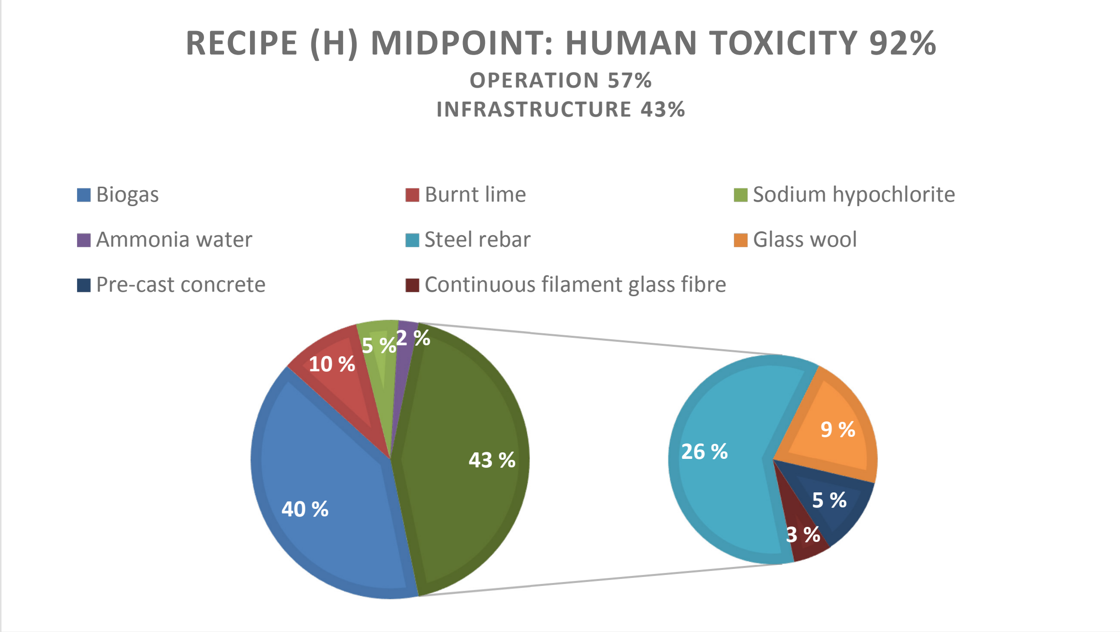


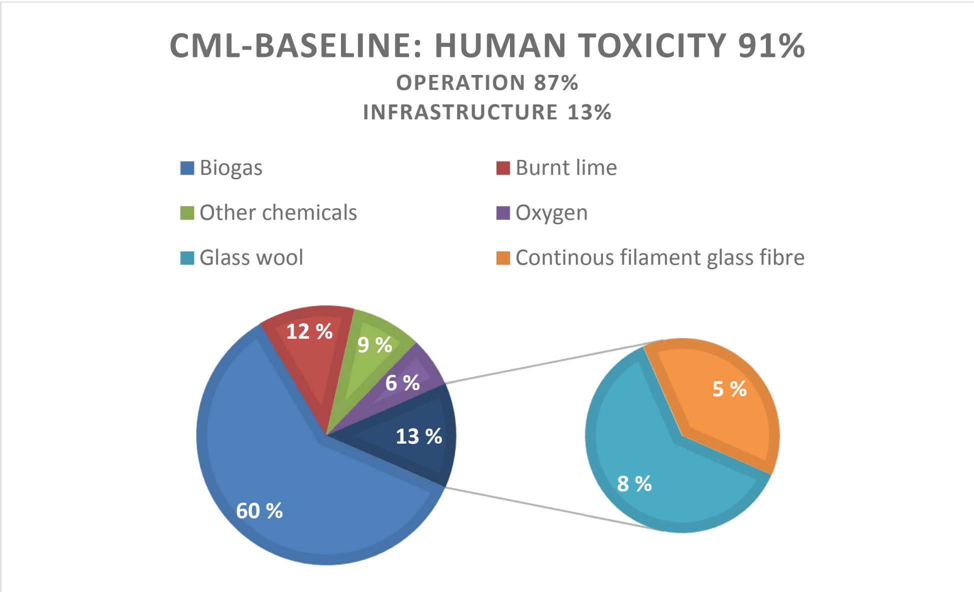
Appendix XXXV. Marine ecotoxicity with ReCiPe (H) Midpoint and CML-Baseline (further analyzed from OpenLCA-results).



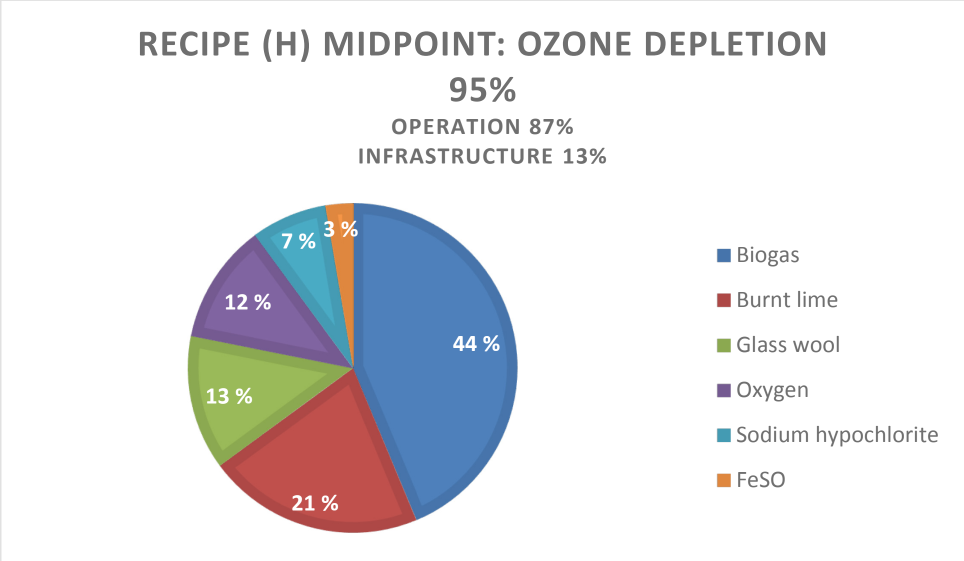


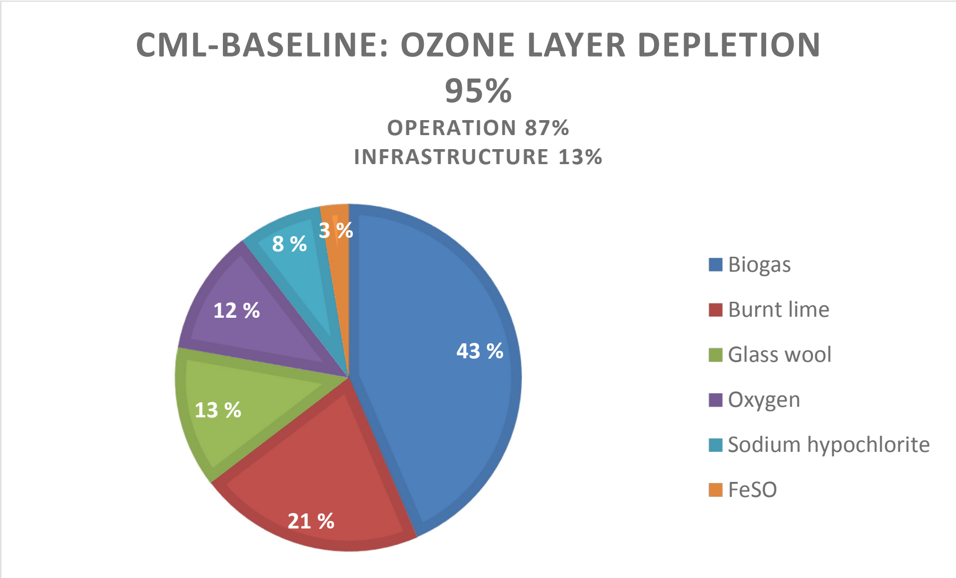
Appendix XXXVI. Human toxicity with ReCiPe (H) Midpoint and CML-Baseline (further analyzed from OpenLCA-results).



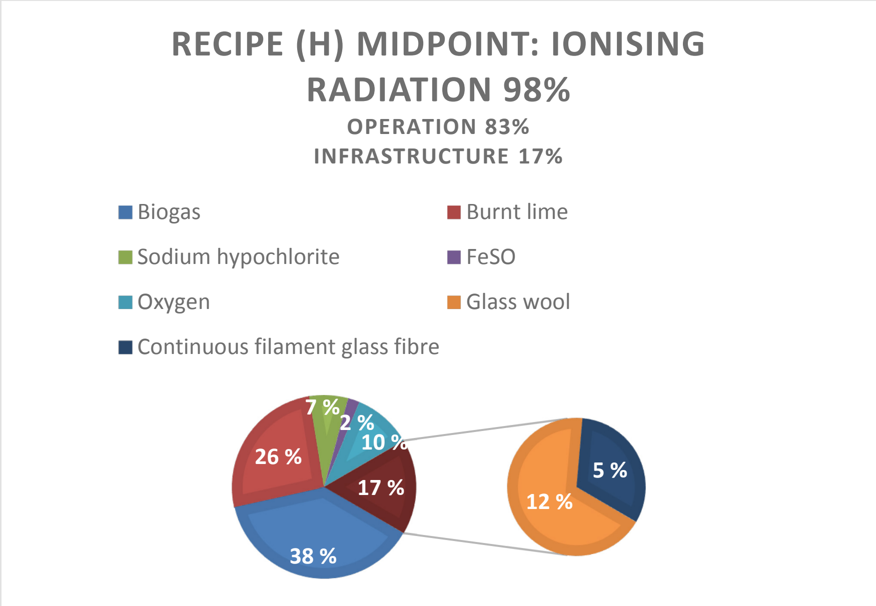


Appendix XXXVII. Ozone depletion with ReCiPe (H) Midpoint and CML-Baseline (further analyzed from OpenLCA-results).

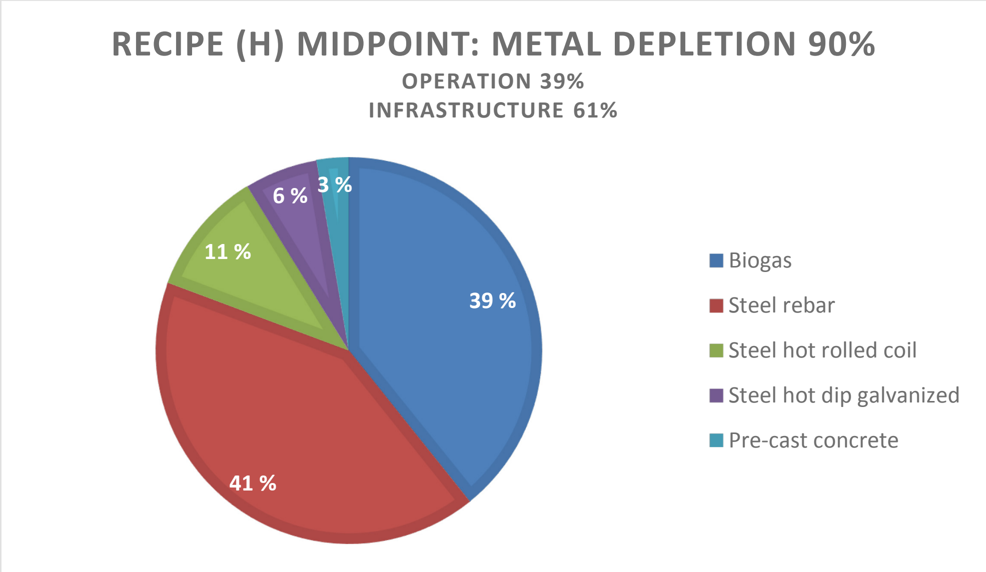


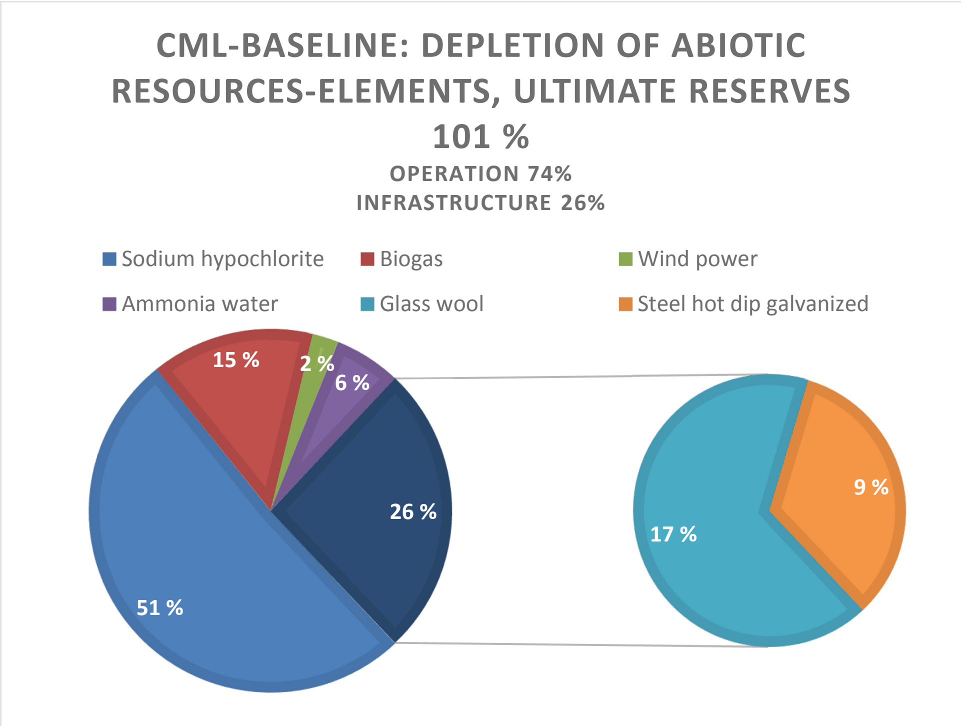


Appendix XXXVIII. Ionizing radiation with ReCiPe (H) Midpoint (further analyzed from OpenLCA-results).



Appendix XXXIX. Metal depletion with ReCiPe (H) Midpoint and depletion of abiotic resources-elements ultimate reserves with CML-Baseline (further analyzed from OpenLCA-results).





Appendix XL. Marine eutrophication with ReCiPe (H) Midpoint and CML-Baseline. (further analyzed from OpenLCA-results).